X-576-67-264

NASA TM X- 63058

PRELIMINARY PERFORMANCE ANALYSIS OF HIGH-SPEED DIGITAL DATA CIRCUITS IN THE NASCOM NETWORK

REVISED
AUGUST 1967

GPO PRICE $ ____

CFSTI PRICE(S) $ ____

Har copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

NASA — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

FACILITY FORM 602

N68-13826 (ACCESSION NUMBER) (THRU)

54 (PAGES) 1 (CODE)

TMX-63058 (NASA CR OR TMX OR AD NUMBER) 07 (CATEGORY)

87-48573

X-576-67-264

PRELIMINARY PERFORMANCE ANALYSIS OF HIGH-SPEED DIGITAL DATA CIRCUITS IN THE NASCOM NETWORK

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Revised
August 1967

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Greenbelt, Maryland

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PRELIMINARY PERFORMANCE ANALYSIS OF HIGH-SPEED DIGITAL-DATA CIRCUITS IN THE NASCOM NETWORK

INTRODUCTION

The National Aeronautics and Space Administration (NASA) communications network, known as NASCOM, consists of operational communications lines and facilities for transmitting mission-related information used to conduct NASA programs and projects. The basic NASCOM arrangement furnishes all NASA mission-control, technical-control, and computation centers with access to remote tracking, data-acquisition, and command stations. This access, primarily for launch, insertion, orbital flight, deep space flight, and recovery operations, is provided by communications channels routed through the primary NASCOM switching center at the Goddard Space Flight Center (GSFC) and the remote NASCOM switching centers. The primary switching center provides centralized communications operations and control and, in conjunction with the remote switching centers, enables primary circuit-sharing on costly overseas-circuit facilities to the maximum degree consistent with meeting NASA mission requirements.

The origins of NASCOM may be traced to Project Vanguard in early 1958, when point-to-point teletypewriter services were established to locations in Africa, South America, and Australia. In early 1961, the Project Mercury Network comprising radar tracking, telemetry, and command stations was established with centralized communications-control facilities located at the Goddard Space Flight Center in Greenbelt, Maryland. This network included full-period point-to-point leased teletypewriter and voice circuits which interconnected the tracking stations with the control and computation centers.

The growth of the space program led to three tracking and communications networks: The Space Tracking and Data-Acquisition Network (STADAN), for support of unmanned scientific satellites in close orbit (between the earth and the moon); the Deep Space Network (DSN), for unmanned scientific spacecraft performing missions near or to other planetary bodies in the solar system; and the Manned Space Flight Network (MSFN), for manned spacecraft.

The nature of new programs and missions required frequent additions to and modifications of the tracking networks, and the introduction of centralized spacecraft command and control required highly reliable communications services. The combination of reliability requirements and economic considerations created a compelling need to combine and share the communications facilities of the STADAN, DSN, and MSFN networks. This led to the NASCOM concept of a primary switching center and several secondary switching centers to provide circuit-sharing facilities, flexibility, and combined communications management and control of all operational ground-communications systems. Through consolidation, total NASA communications resources became available for use by any mission, with alternate communications channels available in case of isolated circuit malfunction.

The global NASCOM system now contains more than one million miles of transmission services, including 400,000 circuit miles of teletype facilities; 140,000 circuit miles of voice-only telephone facilities; 450,000 circuit miles of alternate voice/data telephone facilities; 10,000 circuit miles of data-only telephone facilities; and 10,000 circuit miles of wideband facilities, all operating on a full-period basis. More than 100 locations engaged in NASA support activities throughout the world are served by various combinations of these services.

The high-speed data-transmission portion of NASCOM uses voice-bandwidth channels in an alternate voice/data mode. A number of tests have been conducted on many of these channels since mid-1966 to determine both their short-term and long-term behavior. Many of these tests were conducted regularly as part of a program of continuous channel-performance surveillance; other tests (for phase jitter, for example) were conducted specifically for the purpose of obtaining information on a single characteristic of channel behavior. All the channels for which performance is described are four-wire full-period voice-bandwidth data-quality services. Most of the channels discussed are trans-oceanic cable services which may come under the jurisdiction of several common carriers and may extend to 12,500 statute miles in length. Some information is presented on communications-satellite data-transmission services.

This paper represents a unique assembly of data-channel performance information, because nearly all the tests have been conducted on extremely long-haul combinations of private-line services. As the test results show, simple extrapolation of domestic channel performance is not adequate to describe the characteristics of such long-haul services. A previous paper[1] contains details on the configuration and characteristics of data-transmission equipment used in NASCOM.

PRESENT STATUS OF NASCOM

Data Channels

Figures 1 through 3 show the present extent of operational voiceband data-grade services (AT&T/Schedule 4B Design Goal or equivalent, Table 1) in NASCOM. Table 2 summarizes the number of circuits by geographic area.

Some of the channels listed in Table 2 are arranged in tandem to provide data-transmission services over longer distances than are feasible with single channels meeting the 4B design goal. Regenerative data-signal repeaters at all locations where 4B channels interconnect prevent the accumulation of large amounts of signal degradation. The previous paper[1] treated this subject in detail. An example of such a circuit is the one from GSFC to Carnarvon, Australia, which consists of three 4B segments: GSFC to Honolulu, Hawaii; Honolulu, Hawaii, to Canberra, Australia; Canberra, Australia, to Carnarvon, Australia. Regenerative repeaters are located at Honolulu and Canberra.

When different communications carriers provide portions of a circuit for which end-to-end 4B characteristics are desired, the carriers have agreed among themselves how the technical specification for the channel should be divided. Typically, individual sections of such a channel may be provided in accordance with "one-half" or "one-third" of the 4B design goal.

One method for developing fractional Schedule 4B equalization limits recognizes that the shape of the Delay vs. Frequency characteristic is quite similar for different channels and hence accumulation of delay degradation will be nearly linearly related to the number of tandem sections in the overall circuit. Attenuation vs. Frequency characteristics tend to be considerably less similar for different channels and consequently accumulation of amplitude equalization degradation will normally be less rapid. In this method, the fractional delay limit is calculated proportional to the appropriate fraction (an additional 10% of delay is allowed since the delay curves are most probably not identical) while the fractional amplitude limit is calculated proportional to the square root of the appropriate fraction. This method is convenient since it allows calculation of fractional equalization limits for any Schedule 4B fraction. Figures 4 and 5 illustrate fractional Schedule 4B equalization limits established with the above method and compare these limits with the Schedule 4B and 4C design goal limits.

In fixing the design goal for different sections of a circuit, consideration is given to the relative quality and capability of the respective sections. Thus, the section routing via submarine cable may be allowed two-thirds 4B for equalization but perhaps only one-third 4B for impulse noise, while the microwave-derived

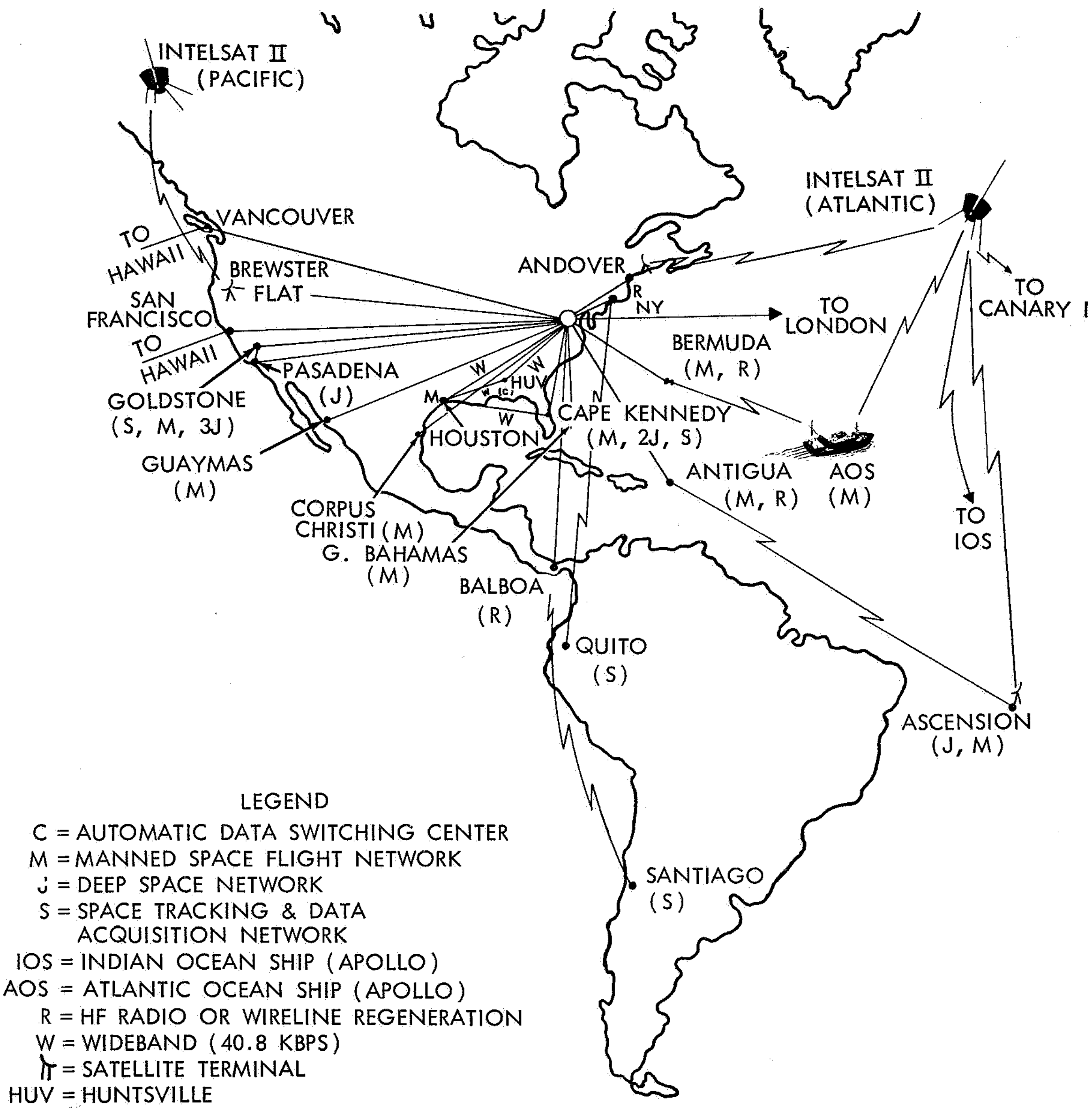


Figure 1. High-Speed Data Communications Network, North and South America

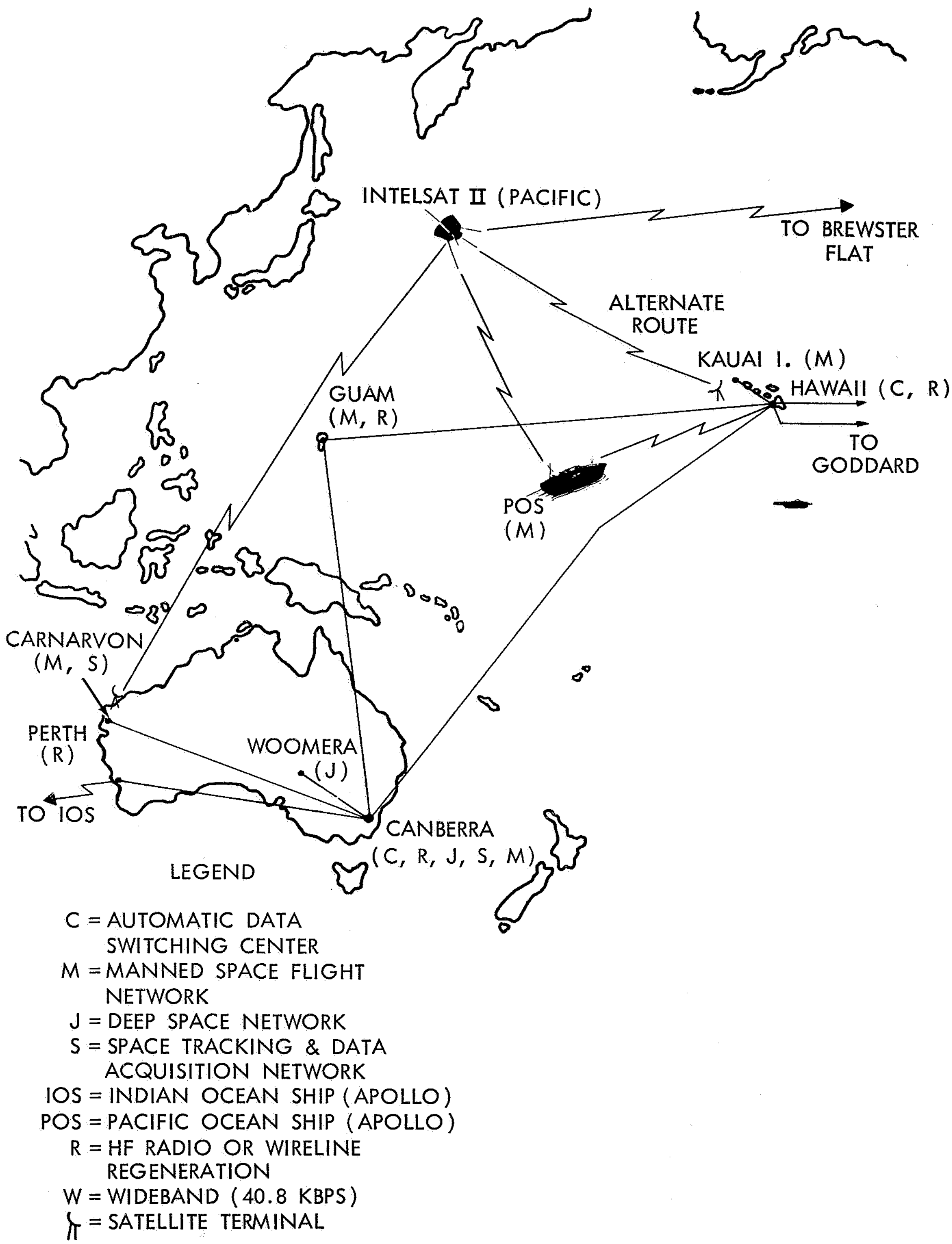
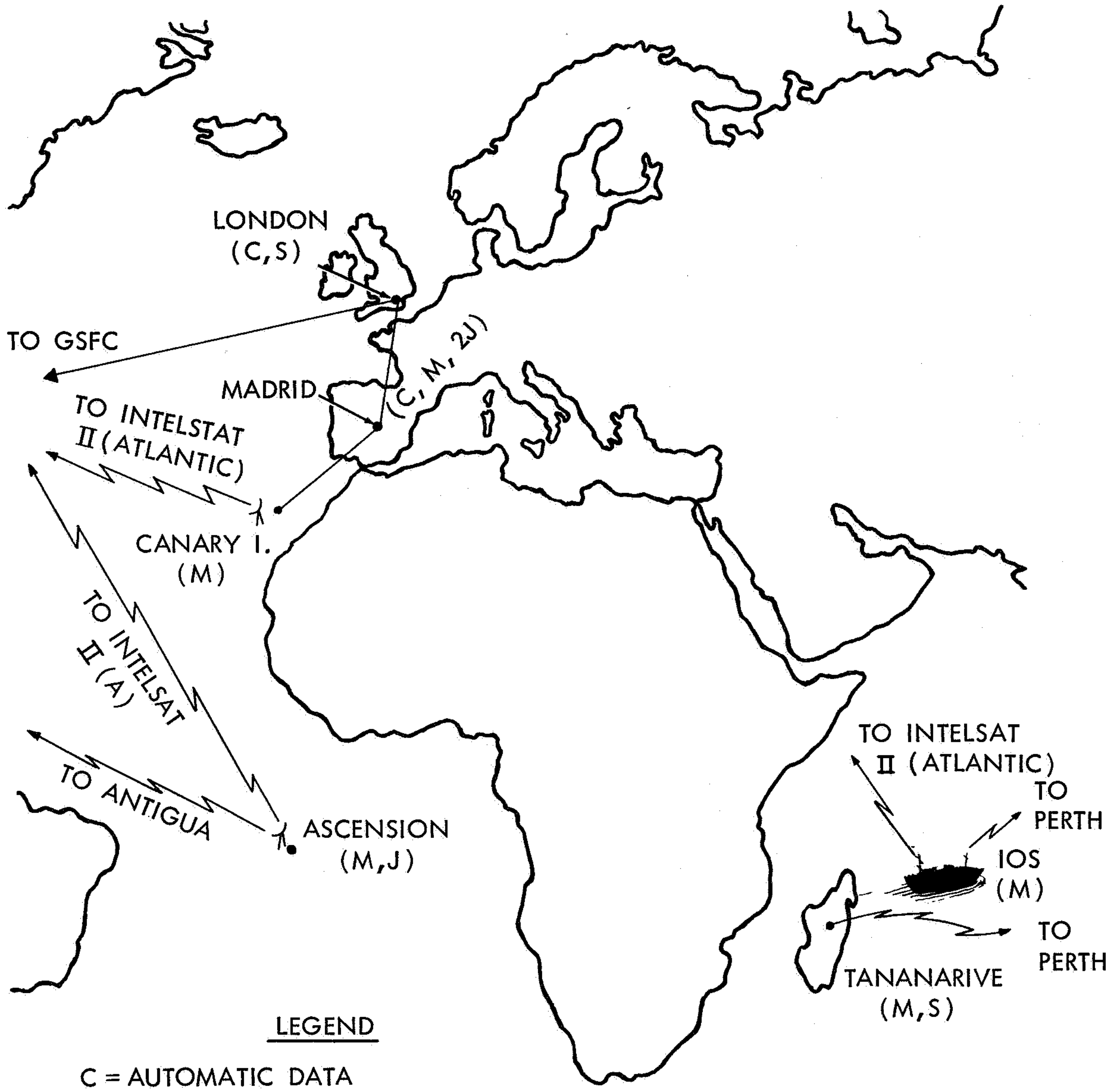


Figure 2. High-Speed Data Communications Network, Pacific Area and Australia



LEGEND

C = AUTOMATIC DATA SWITCHING CENTER
M = MANNED SPACE FLIGHT NETWORK
J = DEEP SPACE NETWORK
S = SPACE TRACKING & DATA ACQUISITION NETWORK
IOS = INDIAN OCEAN SHIP (APOLLO)
R = HF RADIO OR WIRELINE REGENERATION
W = WIDEBAND (40.8 KBPS)
= SATELLITE TERMINAL

Figure 3. High-Speed Data Communications Network, European and African Area

Table 1

Characteristics of AT&T Data-Channel Specification and CCITT M. 89 Recommendation

CHARACTERISTIC SPECIFIED	AT&T 4B DATA CHANNEL DESIGN GOAL	CCITT RECOMMENDATION M. 89
ATTENUATION CHARACTERISTICS		
Max. attenuation variation with time: (at 1000 Hz for 4B, at 800 Hz for M. 89)	±3 db short term (measurement interval) ±4 db long term (seasonal, tube aging etc.)	±3 db short term (a few seconds) ±4 db long term (daily and seasonal variations)
Max. attenuation variation with frequency (reference 1000 Hz for 4B, 800 Hz for M. 89)	300-499 Hz -2 to +6 db loss 500-2800 Hz -1 to +3 db loss 2801-3000 Hz -2 to +6 db loss	300-499 Hz -2 to +6 db loss 500-2800 Hz -1 to +3 db loss 2801-3000 Hz -2 to +6 db loss
ENVELOPE DELAY DISTORTION	1000-2600 Hz: Less than 500 microseconds 600-2600 Hz: Less than 1500 microseconds 500-2800 Hz: Less than 3000 microseconds	Specified by means of limits plotted on a graph and if a parabolic envelope delay characteristic is assumed, limits are identical with AT&T schedule 4B.
FREQUENCY ERROR	±10 Hz	Not specified
NOISE CHARACTERISTICS		
Message noise (white noise)		"under study"
Alternate Voice/Data	1500-2500 miles: 43 dbrnC0 2500-4000 miles: 45 dbrnC0	
Data only	54 dbrnC0	
Impulse noise	90 counts in 1/2 hour @ 68 dbrn0, VB weighting	"under study"

Table 2
Geographical Distribution of Data Circuits

Geographic Area*	Number of 4B Ckts	Total Circuit Miles
Atlantic/European	42	115,500
Pacific/Australia	57	189,200
North & South America	11	26,500
Domestic	86	115,500
	Total	446,700

*Channels have one or both terminations within the respective area except for domestic, where both terminations are within the continental U.S.

Table 3
Geographical Distribution of Data Systems

Geographic Area	Terminal Systems	Regeneration Systems
Atlantic/Europe	9	5
Pacific/ Australia	14	6
North & South America (outside continental U.S.)	1	0
Domestic (within continental U.S.)	14	2

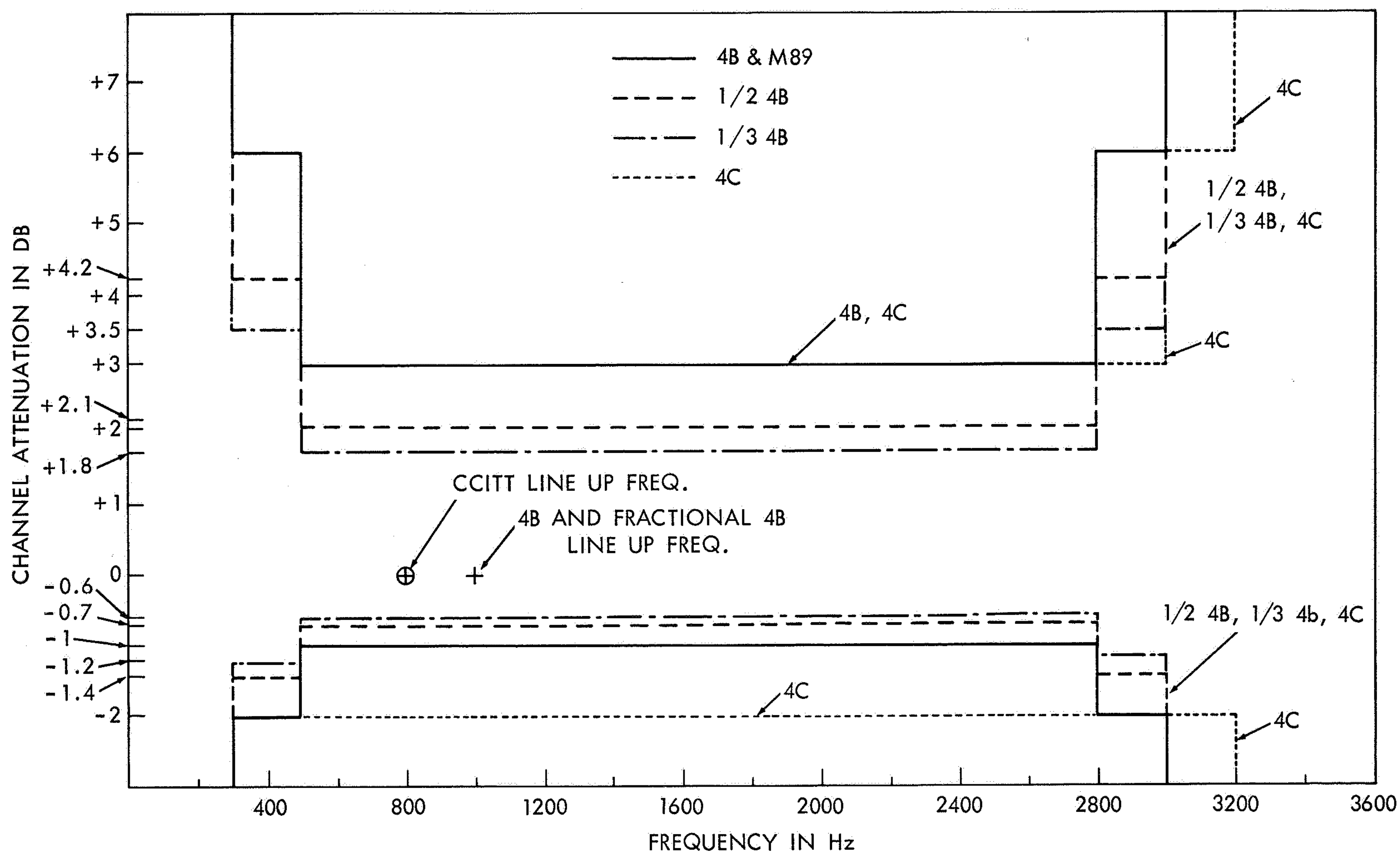


Figure 4. Amplitude-Equalization Requirements for Data Circuits

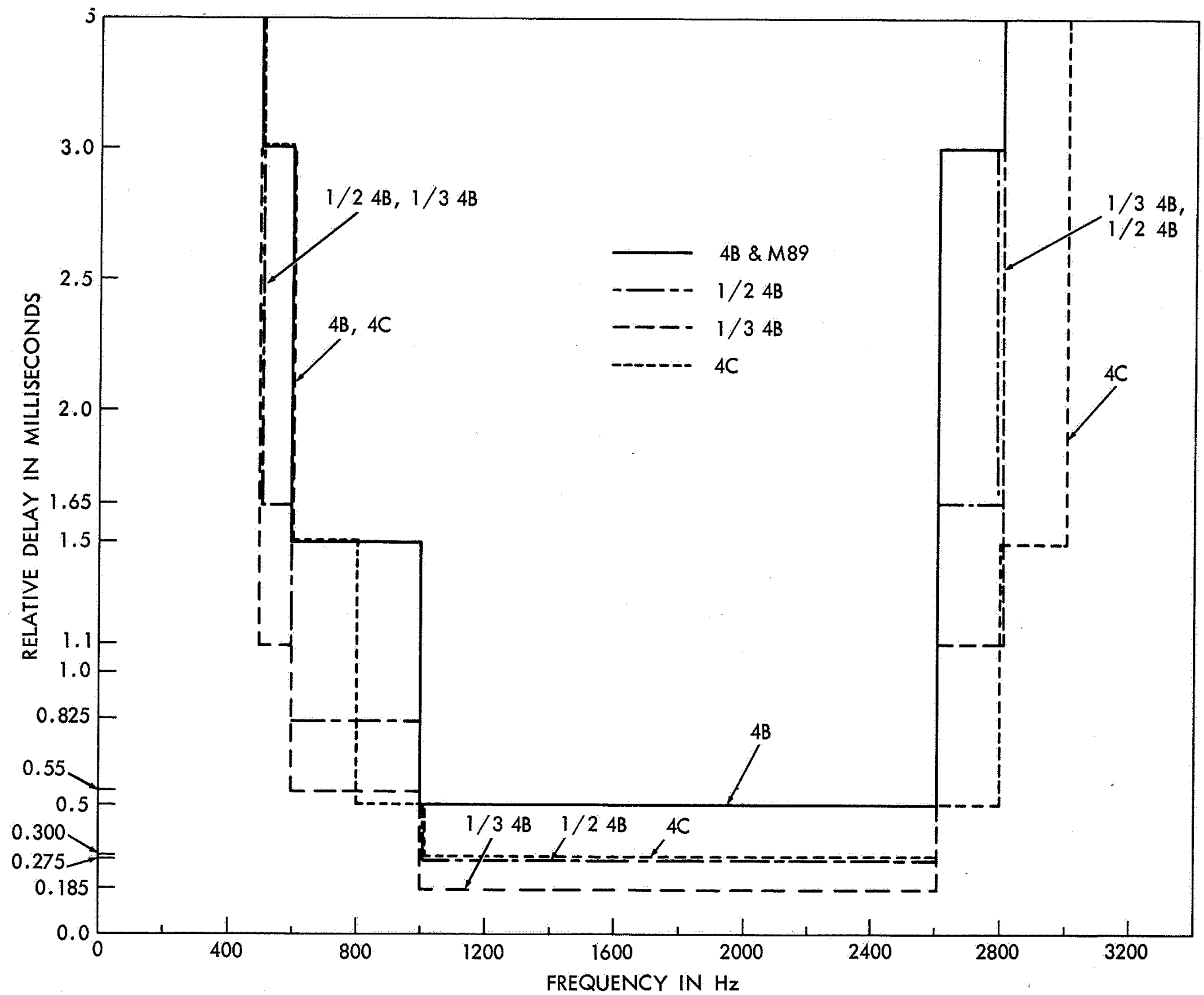


Figure 5. Delay-Equalization Requirements for Data Circuits

end link may be allowed only one-third 4B for equalization. This procedure requires a considerable degree of cooperation among the carriers serving the NASCOM network. Their willingness to operate in this manner has been instrumental in the successful establishment of extremely long-haul, yet reliable, data-communication services.

Data Equipment

High-speed data-transmission and regeneration systems capable of operating at 2400 bits per second (bps) are now in service in the quantities and with the distribution indicated in Table 3. These locations are identified with appropriate symbols in Figures 1 through 3. For any further detail the reader is again referred to Reference 1. All data modem equipment used in the continental United States and in Hawaii is leased from the appropriate Bell System operating company. Equipment at all other locations is owned by NASA.

The data modems[2,3] used throughout the NASCOM system for 2400-bps data transmission are full-duplex modems using four-phase modulation to transmit serial binary data over four-wire voiceband facilities. This data set can operate at 600, 1200, or 2400 bps independently in each direction of transmission. Two data sets, back-to-back, can be used as a regenerative repeater. Synchronous transmission is accomplished with a maximum allowable bit timing speed error of 0.01 percent. Differentially coherent four-phase modulation is used on an 1800-hz carrier frequency, resulting in a line-signal spectrum essentially confined to a band extending from 750 to 2850 hz.

Mission Support Considerations

Since mid-1966, the NASCOM network has successfully supported five deep-space missions (Lunar Orbiters 2, 3 and 4, and Surveyors B and C) and two Apollo network mission simulations with worldwide high-speed data services. Including prelaunch network simulations, the high-speed data support for Lunar Orbiter and Surveyor missions encompassed periods of about 1 month each. Each Apollo mission simulation has required nearly continuous data-transmission support for about 5 weeks. Some of the deep space missions were supported using 1200-bps data rates, but all Apollo activity has been carried out at 2400 bps. From five to twelve data-terminal systems with associated data lines to GSFC were involved in providing the required mission and network support.

Data transmitted during these activities consisted primarily of spacecraft telemetry data received at the tracking stations directly from the spacecraft and reformatted for transmission by synchronous data services to GSFC. Some tracking-data and command-data transmission was also performed during activities related to the Apollo program.

In addition, full-period full-duplex 2400-bps services (one each during non-mission periods, two each during missions) have been in operation between GSFC and London, England, and between GSFC and Canberra, Australia, since August 1966 and December 1966 respectively. These channels provide compacted (multiplexed) teletype-signal interchange between the prime NASCOM switching center at GSFC and overseas switching centers located in London and Canberra. These circuits operate around the clock.

In general, achievement of NASA mission objectives frequently depends upon the data-transmission capability of NASCOM. This is particularly true of the manned flight program, in which the concept of remote-site operation has been expanding rapidly. Most tracking-station activity in support of manned missions is under the direction of flight controllers at the Manned Space Flight Center in Houston, Texas. All data necessary for making decisions on potential modifications to the flight plan are transmitted in real time over high-speed data facilities to the control center at Houston, where the appropriate decisions are made. Instructions based on these decisions may then be sent back to the tracking station in the form of high-speed command-data messages.

A somewhat similar situation exists for DSN and STADAN which requires transmission of selected spacecraft telemetry data (attitudes, battery voltages and currents, temperatures, etc.) to GSFC in real time to allow rapid assessment of spacecraft conditions. This is particularly important during launch and early-orbit phases of a mission. When these mission-control activities are located remotely from the tracking stations, the availability and reliability of the interconnecting data-transmission services may significantly affect the success of the mission.

Preparation for a period of mission-support activity includes performance of complete system simulations which exercise the tracking-station equipment and procedures, the communications network, and the control centers. The tracking stations normally use tape recordings of typical spacecraft data to simulate actual tracking and data-acquisition activities. These exercises, or simulations, may last for one or two days in the case of smaller unmanned scientific spacecraft, or as long as 2 weeks, repeated two or three separate times, for an Apollo mission.

During actual mission support, each tracking station and control center is connected with the central communications center at GSFC by multiple data-transmission services which follow geographically diverse routes wherever possible. The communications carriers may also be asked for "special" or "critical" circuit supervision to assure rapid restoration of service in case of leased circuit or leased equipment failure.

CHARACTERISTICS OF TRANSMISSION CIRCUITS

Table 1 lists the salient characteristics of the AT&T Schedule 4B Design Goal[4] and the C.C.I.T.T. M.89 data channel recommendation[5].

Although attenuation and delay distortion limits are quite specific for a 4B circuit, the noise specification is relatively imprecise, and some circuit characteristics of interest are not specified at all. This is not meant as a criticism of the 4B design goal, which does reflect the state of knowledge of circuit behavior and the test equipment available at the time it was written.

Attempts to raise data rates above 2400 bps have highlighted a need for a more detailed knowledge of transmission-circuit behavior. The extension of transmission into more critical fields (the NASA manned flight tracking network, for example), has made it necessary to know more about circuit characteristics and in particular the nature and distribution of error bursts. The following data-system characteristics are of interest to the transmission engineer and the data system engineer.

Attenuation At Line-Up Frequency

This is specified in 4B and M.89 and is complicated only by the difference in lineup frequency used in the U.S. and in Europe (1000 hz and 800 hz respectively).

Frequency Response

This is specified for 4B and M.89 circuits, and is complicated only by the difference in the frequency used as a reference (same as above).

Variation of Attenuation With Time

4B and M.89 specify a "short-term" and a "long-term" variation in the attenuation at line-up frequency. "Short-term" and "long-term" are not defined precisely, nor are the variations at frequencies other than lineup frequency specified. No attempt is made to specify the rate-of-change of attenuation at the reference or at any other frequencies. This characteristic is relevant to the design of automatic gain-control systems and automatic equalizers.

Slope of Attenuation Characteristic

A specification of attenuation limits with respect to frequency does not of itself control the rate-of-change of attenuation with frequency. For systems using automatic equalizers, this can be of more interest than the actual attenuation.

Absolute Delay

The absolute (propagation) delay is not specified for any leased services, and it would not be realistic to specify this characteristic since it depends upon the method by which the circuit is derived. As it is sometimes important to know the value of absolute delay for a circuit, an accurate method of measurement is desirable.

Envelope Delay

4B and M.89 have similar limits over the 500- to 2800-hz frequency range if an envelope delay characteristic having parabolic properties (increasing delay towards band edges) is assumed.

Variations of Envelope Delay With Time

There is no specification on allowable changes of the envelope delay characteristic beyond the requirement that the envelope delay should never exceed the limits set in the 4B design goal. Slow changes in the delay characteristics have little effect on modem performance when transmitting data at 2400 bps, but would reduce the usefulness of a circuit for transmitting time-reference signals or transmitting data at much higher speeds. The prime reason for concern with the rate-of-change of delay over the band of interest is because automatic equalizers must be designed to track the changes which occur.

Frequency Offset

The 4B design goal allows a frequency error of 10 hz. However, efforts are made to keep offset below 2 hz on any connection within the U.S. Links in tandem may have offsets which are all in the same direction, so that the overall frequency offset for a multiple-segment channel may exceed 10 hz. In practice, the exact magnitude of the frequency offset is rarely a limiting factor of data-system performance; a demodulation system which will tolerate any offset at all will usually handle an error of 20 hz or more.

Frequency and Phase Instability

Rapid (unwanted) changes in the phase of a received signal are frequently referred to as phase jitter (or incidental FM). This characteristic, which can be either periodic or incremental, has been found to have a significant effect on the performance of modems operating at rates from 7200 to 9600 bps on voiceband data circuits. However, neither the 4B design goal or the M.89 recommendation place a limit on phase instability.

Phase instability could perhaps be specified as peak phase-change per unit of time. But of greater interest and of more general application is the rate-of-change of phase which can be expressed as frequency offset (either instantaneous or continuous) from the reference frequency. The difference between phase jitter and frequency offset is not that of the fundamental nature of the phenomenon but the terms in which it is described are usually chosen on the basis of the cause of the perturbations and of the time constants associated with the effects. However, there is probably no need to separate these effects for the purpose of specifying a circuit. One figure—peak frequency deviation or maximum rate-of-change of phase—could serve the purpose if a short measurement time is chosen. Some period related to the bandwidth of the circuit would be desirable, and the time interval of one signalling element, based on the Nyquist rate, might be appropriate.

Another parameter which relates to phase and frequency perturbations and which can be identified and specified is the periodicity of the deviations; this seems to have a significant effect only on the rate of deviation of phase from a reference tone, and can be specified independently.

Random Noise

The 4B design goal prescribes a limit for random noise which is to be measured on an instrument with a C message-weighting characteristic. The C weighting, however, was designed to measure the disturbing effect of noise on human observer using a certain telephone set, and is probably not particularly applicable to voiceband data circuits. However, the performance of modems designed to date has not been limited by random noise, and at the present state-of-the-art the 4B limit for random noise can be considered acceptable.

Impulse Noise

Impulse noise is specified in the 4B design goal in terms of the readings on a Western Electric 6A impulse noise-measuring set. As this device cannot count impulses which occur less than 100 milliseconds apart in time, the reading is not necessarily a representative measure of the number of errors actually caused by impulse noise. If all circuits had similar impulse noise patterns, the 6A noise set reading would have meaning as a means of comparing circuits, but there is no evidence that this similarity exists. Yet, for want of a better instrument in widespread use, and because the specification calls for it, measurements using the 6A impulse noise-measuring set (or other test sets with identical dynamic characteristics) are adopted.

Bit Error Rate

The term "bit-error rate" (BER) is defined as the number of bits in error received in a chosen time interval divided by the total number of bits received in that time interval. The BER is useful for long test intervals (such as 24 hours) as an indication of the long term performance of a circuit.

This expression, however, has limited significance for short time intervals unless more is known about the distribution of the errors in the data. For example, if most of the error-bits where known to be randomly distributed, the BER would be a meaningful parameter for evaluating and comparing circuit performance for almost any time interval chosen. The distribution of errors in wireline data channels, however, are characterized predominantly by burstiness and to a lesser extent by their periodicity. In these cases the BER has significance only in comparing similar channels to one another, and comparing a channel to itself as it changes in time.

The error distributions characterize a data channel and determines its usefulness for transmitting data of different formats and in different modes. In order to optimize a data-transmission system (e.g., to choose the optimum block length in an automatic block retransmission system, or to choose the optimum code for a forward error detection/correction system), the statistical distribution of the occurrence of errors is needed. Such attempts to measure and express error characteristics have been made[6, 7, 8] by taking a bit-by-bit record of the time in which errors occurred during test data runs, and processing this record to obtain a statistical description of the randomness, burstiness, and periodicity of the errors.

Circuit Outages

Any circuit will exhibit periods of unsatisfactory service caused by unforeseen degradation of transmission characteristics. Preventive maintenance should not be a problem in this respect because a time can usually be chosen when the availability of the circuit for transmitting data is not essential. Circuit failure may occur when the transmission characteristics go outside Schedule 4B design goal limits; this can happen suddenly and be restored just as suddenly, or may result from a slow drift of the characteristics beyond the 4B limits. Many instances of failure might be forestalled if the appropriate circuit parameters were continuously monitored, but so far the monitoring equipment is not available nor has sufficient experience been accumulated upon which to base predictions. Two approaches are possible:

(a) Monitor the transmission characteristics to detect any significant trends which might be occurring, and observe these drifts as they approach the limits of the circuit specification. Equipment suitable for this purpose has been announced by one manufacturer[9]. This equipment permits measurement of most circuit parameters in less than 1 second, and could be time-multiplexed with data-transmission equipment.

(b) Monitor error rates and patterns, and use this information to detect a degenerating circuit and to determine the probable cause of the degeneration. Experience in this area is not yet sufficient to give reliable results; but, once the mechanisms of channel failure become understood, it may be relatively easy to institute a program of performance-monitoring because computer equipment connected to data-transmission circuits could be programmed to make this analysis.

Some comment is necessary on what constitutes an outage: If the analog characteristics of the transmission circuit are monitored, most of the phenomena called "outages" would be accompanied by some channel characteristic going outside the specification. But there are some characteristics (e.g., phase instability) which are not specified, but which could certainly lead to a condition which would be called an "outage".

Defining an outage in terms of the bit error rate has pitfalls, too. A time interval during which the error rate falls below an acceptable level must be defined (as must the level which is considered acceptable); for example, an isolated burst of 50 errors on a 2400-bps circuit would not be classified as a 30-minute outage because the average error rate for this period exceeded 1 in 10^5. Furthermore, the type of modem in use will determine whether a perturbation on the circuit produces a sufficient number of errors to justify the name "outage". When it is necessary to define an outage in terms of error rate, a definition such as the following may be acceptable:

> "An outage is considered to have occurred if the error rate had become an order-of-magnitude worse than the acceptable long-term level of performance, and this state had appeared likely to continue until intervention was made to restore the circuit. A period when transmission is impossible (50-percent error rate) is also considered to be an outage unless this break in service had been scheduled beforehand."

Figure 6 shows another and perhaps more flexible method for operationally determining, on the basis of observed bit-error rates, whether or not an outage should be declared and maintenance performed. The line separating the Red and Yellow regions represents the worst-case performance (in terms of bit-error rate) that should ever be allowed to occur during a test period of a particular duration (horizontal axis). If, as the result of any single test, or as the result of an accumulation of test time (hopefully randomly distributed), a point is located within the Red region, an outage should be declared and immediate maintenance undertaken. If a point is located in the Yellow region, additional testing is recommended to determine whether a trend towards either the Red or the Green region results from examination of the new test data.

The authors admit taking considerable liberty in drawing a straight line between Points A and B (the line separating the Red and Yellow regions): the line separating the Yellow and Green regions was also established rather arbitrarily, but resulted from a strong feeling that a Yellow region should be established as a buffer zone between that performance level which the customer would "like" to have and that which the carriers are willing to suggest as "worst-case" performance. However, the significance of Figure 6 rests not in the values chosen, but

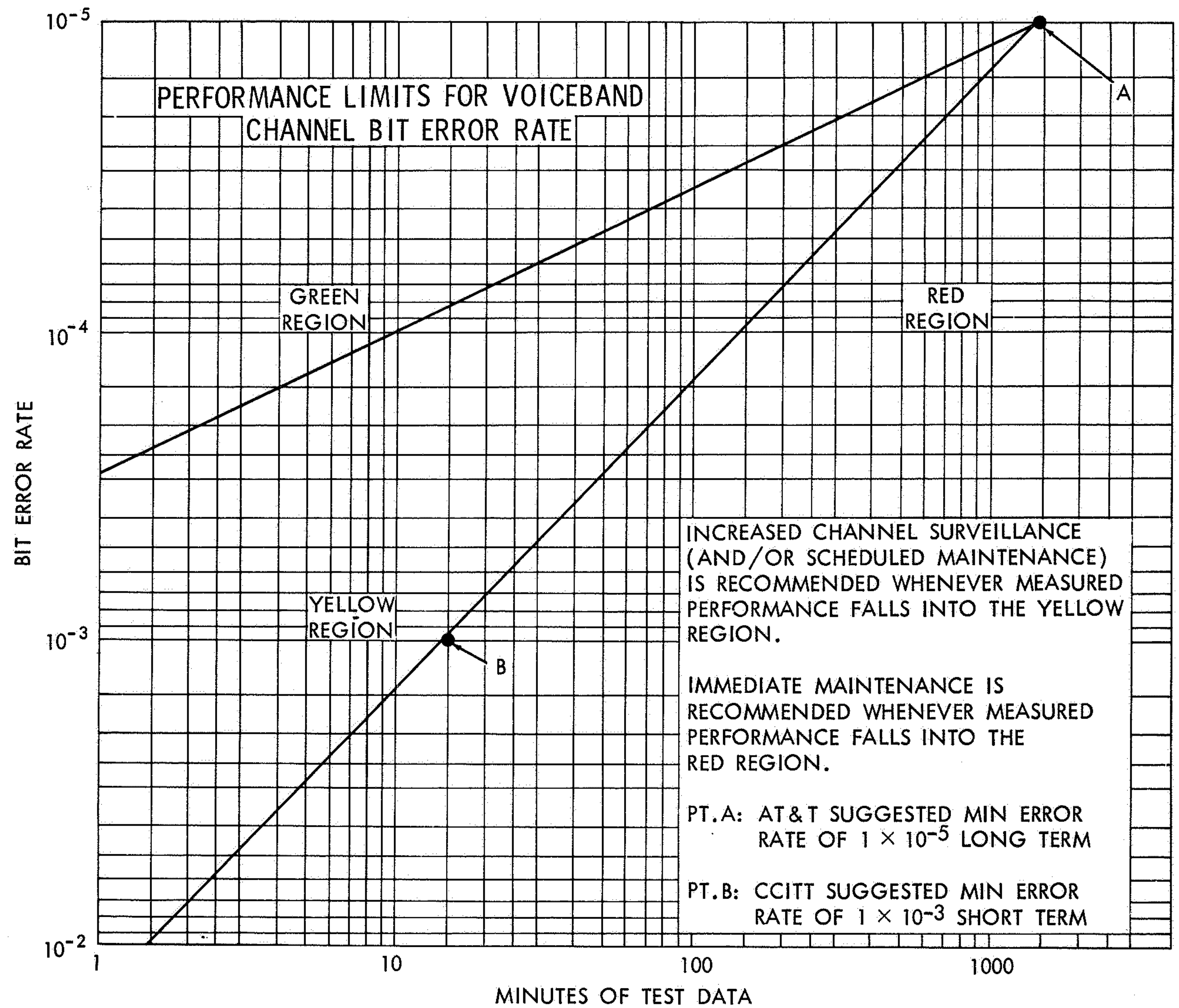


Figure 6. Performance Limits for Voiceband Channel Bit-Error Rate

in the recognition that short-term performance can occasionally be quite bad (the customer should be prepared to accept this) and that long-term performance should be quite good.

A simple statement of a long-term bit-error rate capability is not sufficient to satisfy operational requirements, because it is not feasible to wait for the conclusion of a 24-hour test, for example, before establishing that a channel is behaving below acceptable performance limits. Whether or not the short-term performance of the type of channel typically used in the NASCOM network is at all representative of the long-term performance remains to be seen.

DATA-COLLECTION METHODS

Data for checking NASCOM circuit performance have been collected in several ways. Operating procedures have included a program of routine checks on some transmission characteristics since November 1966. These tests, performed approximately once each month, consist of measuring the line level, amplitude response, envelope delay, and impulse noise in each direction of every duplex circuit. Also, a BER measurement is made on a short run of pseudo-random test data for both the transmit and receive sides of the channel. Long-term error-rate tests have been made, and tests for the frequency and phase instability of some circuits have been performed in the past several months. The following paragraphs describe the actual test methods.

Attenuation At Lineup Frequency

The line level (net loss) is measured at 1000 hz with the Hewlett-Packard 3550A test set. This instrument consists of a VTVM, a sinewave signal generator, and a patchpanel for attenuation and bridging purposes. A 1-khz test tone from the signal generator is adjusted to local test tone level and put on the line at the transmitting end. At the receiving end the circuit is terminated in 600 ohms and the level is read on the VTVM. The same procedure is repeated for the other direction of the circuit. Measurement accuracy of this test set-up is ±0.5 db.

Amplitude Response and Envelope Delay

The amplitude response and envelope delay characteristics are measured using the Acton Laboratories Inc. transmission measuring set type 451-A and 452-A, and the results are automatically and simultaneously plotted using two X-Y plotters. The Acton transmitter modulates the audio frequency carrier with a 25-hz signal derived from a highly stable oscillator. The modulated carrier frequency is then automatically swept from 300 hz to 3 khz at a constant level output and sent through the channel. To determine the envelope delay characteristic, the receiver compares the received 25-hz signal with an internally generated 25-hz reference signal and produces an output voltage proportional to the phase difference between the two signals. The output voltage representing relative delay is plotted on the Y-axis while an analog voltage proportional to the carrier frequency drives the X-axis of the X-Y plotter.

The input power to the receiver is measured directly with a voltmeter since the input impedance is constant at 600 ohms. A voltage proportional to the input power is provided for the Y-axis of a second X-Y plotter which is used to plot the attenuation with respect to frequency. The accuracies of the plots are within ±3 percent on the frequency axis (±90 hz at 3 khz), approximately ±0.5 db on the attenuation ordinate and approximately ±25 microseconds on the delay ordinate.

Absolute Delay

Measurements of absolute delay have been made using a "sounding" technique. A short tone burst (typically of 10-millisecond duration) of a frequency at which channel propagation is most rapid (usually 1500 to 1800 hz) is transmitted through a channel looped back at the remote end. The horizontal sweep of an oscilloscope is started at the time that the tone burst is sent, and the returning tone burst is observed on the oscilloscope. For all practical purposes, except for perhaps timing synchronization applications, the propagation delay of the send and receive sides of the circuit are equal and the one-way delay can be readily determined by dividing by two the loop-back delay as measured on the oscilloscope. By using the oscilloscope delayed sweep feature and making allowances for channel rise time, an overall accuracy of plus or minus 1.5 milliseconds can be readily achieved with this method.

Impulse Noise

Impulse noise is measured with the Western Electric 6A set and more recently with the Northeast Electronics Model TTS 58A. Both units have similar electrical characteristics and the impulse counting resolution is 100 milliseconds. The test involves counting the number of impulses above 68 dbrn0 in one half hour.

Frequency and Phase Instability

Because no standard methods exist for measurements of the amount and the effect of phase jitter in transmission circuits, several different tests were tried with varying amounts of success.

Method 1—In an attempt to measure the magnitude of rapid phase variations directly, a test arrangement was used as shown in Figure 7. A 1000-hz test tone was transmitted through the circuit in which this signal became modulated with noise and phase jitter. The received signal was then applied directly to the X-axis of an oscilloscope. An HP Model 302A wave analyzer which has a band-pass of 1.5 hz and an AFC tracking rate of about 0.5 hz/sec, was used to extract the average carrier frequency. The non-linear phase properties of an electronic filter were used to add additional phase delay to the reference signal to make it an average of 90 degrees out of phase with the untreated received signal. The resulting Lissajou pattern (nominally a circle) continuously varied, the major diameter of which sporadically shifted from 45 to 135 degrees and the minor diameter varied according to the sine of the phase difference. The peak magnitude of the phase jitter in degrees was then calculated from the X-axis or Y-axis crossings of the narrowest oval displayed. This method made it possible to measure the peak amplitude of the jitter fairly easily, but only gave a crude indication of its frequency distribution.

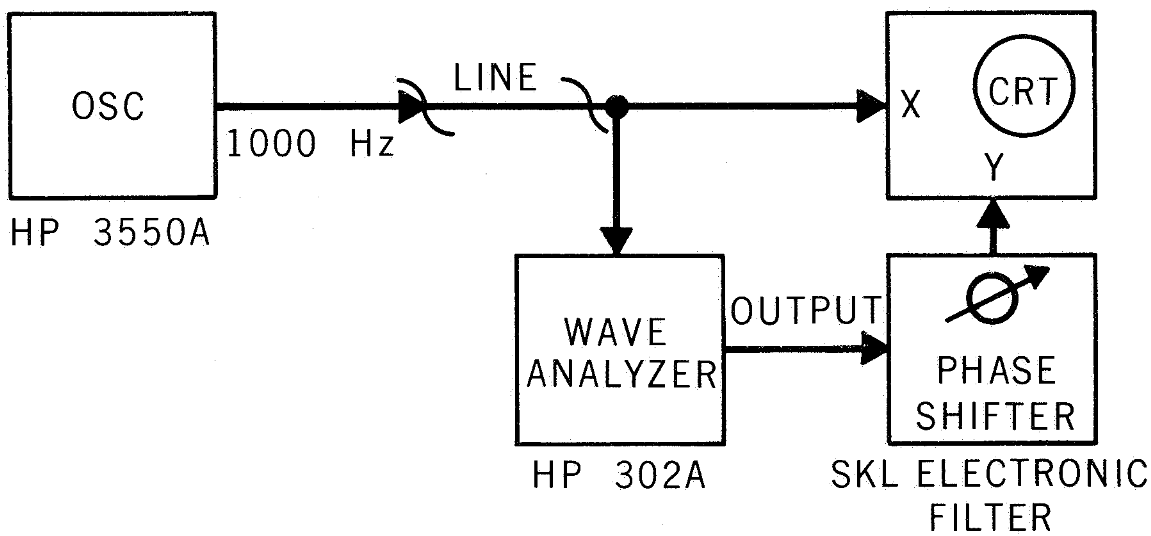


Figure 7. Measurement of Phase Jitter, Method 1

Method 2—To obtain some frequency distribution information, the test set-up depicted in Figure 8 was utilized. Here, the test signal, after transmission through the circuit, was applied to the phase comparator of a telemetry data bit synchronizer. The tracking rate of the voltage-controlled oscillator (VCO) within the synchronizer was limited by a 0.2-hz low-pass filter in the VCO control circuit. The VCO generates a sawtooth voltage which is used as the reference signal in the phase comparator circuit of the bit synchronizer. The phase comparator produces pulses whose amplitudes and polarities are proportional to the phase difference of the reference and line signals. These pulses are smoothed by another low pass filter (3-db cutoff at approximately 100 hz) and plotted using chart recorder.

This method proved to be better than the one described previously, because phase variations with respect to time could now be read from the chart paper. The test was limited to phase jitter peaks of about ±30 degrees because the synchronizer tracking range was severely reduced by the modifications to the tracking loop. The bit synchronizer also lost sinc when there was an abrupt frequency change of 1.5 hz or more. When this happened the synchronizer had to be manually re-synchronized.

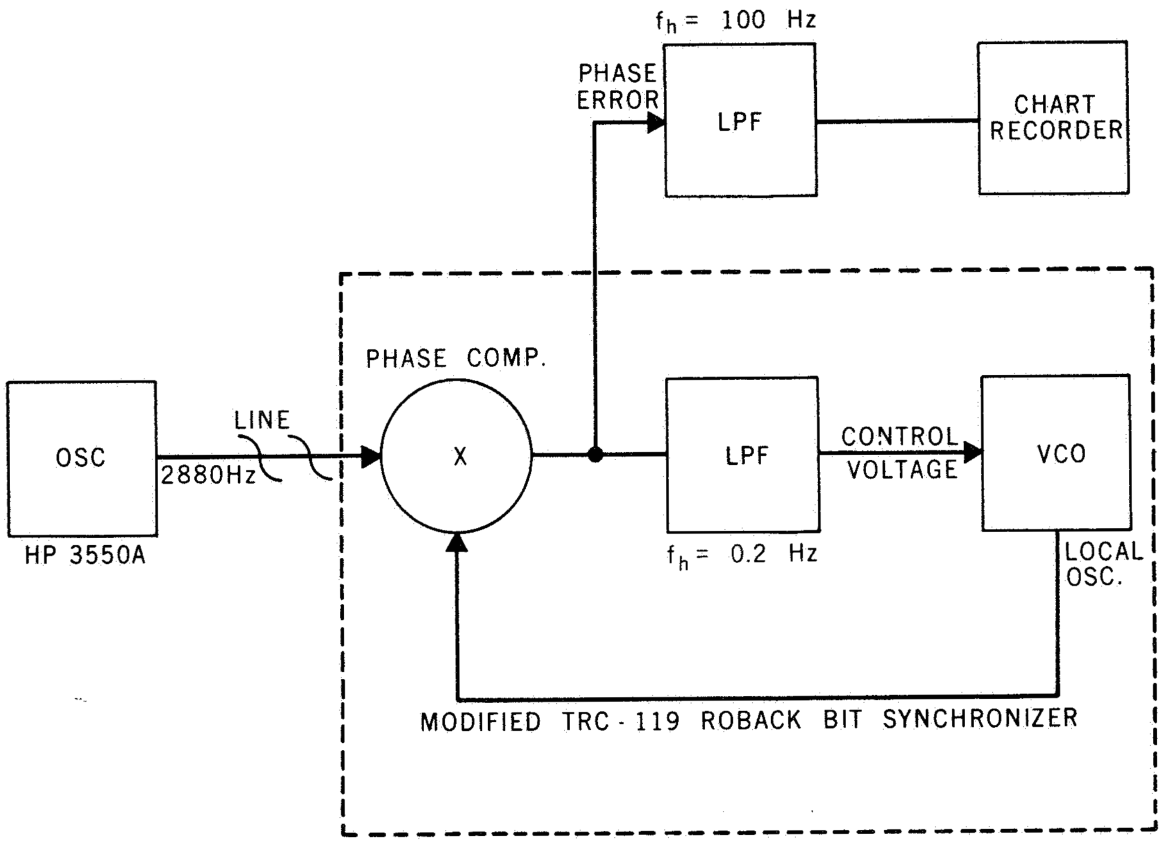


Figure 8. Measurement of Phase Jitter, Method 2

Method 3—The best results were obtained in tests using a MICOM 8100-W flutter meter in an arrangement shown in Figure 9.

The MICOM flutter meter is essentially a highly stable low-noise FM demodulator. The spectrum analysis of the output of this device was made using a Hewlett-Packard 302A wave analyzer and plotted with an X-Y recorder after conversion of the vertical (signal-amplitude) axis to a logarithmic scale. The Appendix gives spectrum analyses of several measurements using a test tone of 2800 hz.

The MICOM 8100-W has a frequency-attenuation characteristic which falls off at about 20 db per octave above 200 hz. The frequency spectra in the Appendix have not been compensated for this. A correction of about 20 db per octave should, therefore, be applied between 200 and 500 hz when reading the plots.

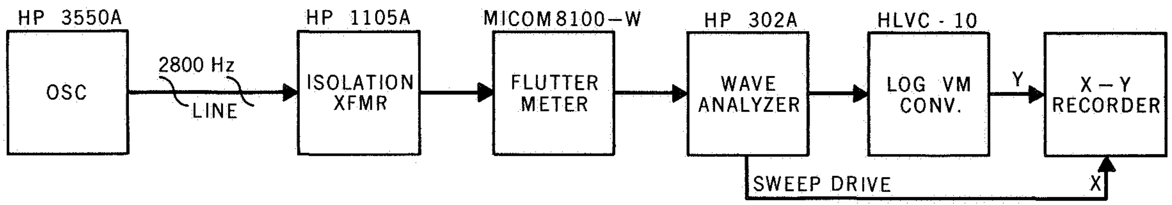


Figure 9. Measurement of Phase Jitter, Method 3

Method 4—The effect of phase shifts on the operation of the Western Electric 205B modem was examined by using the test setup in Figure 10. With this arrangement, the amount of unwanted phase shift in one signal-element time of the 205B (833 microseconds) was measured using a 1200-hz test tone transmitted through a channel. Amplitude modulation may be produced by rapid phase changes on the band limited circuit occurring at the same time that a phase effect is observed, or independently of phase effects. In either case it is desirable to eliminate amplitude effects so the limiter is included. The limiter used reduced amplitude variation by a factor of four. More meaningful results might have been achieved if a greater limiting power had been used.

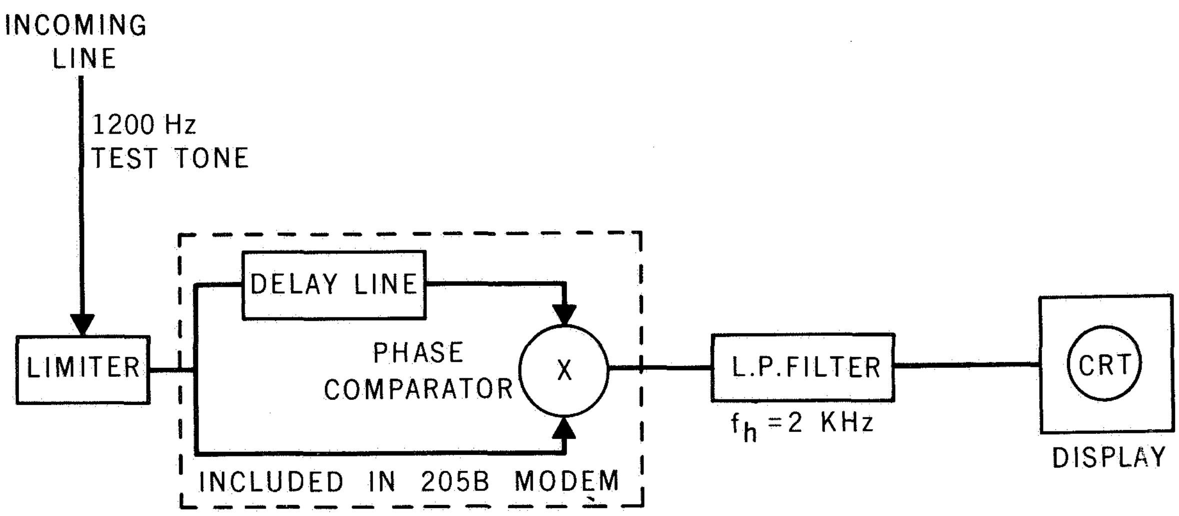


Figure 10. Measurement of Phase Jitter, Method 4

The delay line and multiplier were used to compare the phase of the received signal with that received one cycle earlier. The frequency of the test tone was chosen so that the delay line introduced a delay of exactly one cycle. Any phase shift experienced by the test tone during the time equal to the delay line period appears as a difference in the relative phase of the undelayed and delayed waveforms. The ideal means of detecting this differential is with a multiplier which the detector of the 205B modem approximates. Another reason for using the phase discriminator of the 205B is that the results then give an indication of how a 205B modem would actually react to phase perturbations introduced by the line.

The measurements were made by displaying the 205B modem discriminator output on an oscilloscope and photographing the result. Calibration was effected by switching in known phase discontinuities and noting the deflection on the oscilloscope.

Bit-Error Rate

All bit-error rates were measured with Frederick Electronic Corporation Model 600 data transmission test sets. This set generates a pseudo-random binary-data test pattern, 2047 bits in length, for modulation of the 205B data modem. All tests were conducted at 2400 bps with the data rate controlled either by the internal master oscillator of the data modem or by a crystal oscillator within the test set. All circuits were tested in their normal operational configuration, which requires a regenerative repeater at all points where tandem 4B channels interconnect.

The receiving portion of the test set contains automatic bit- and pattern-synchronization figures, and displays bit-error totals on an electromechanical totalizer with a counting rate of about 20 counts per second. A buffer with a storage capacity of 1540 counts is used to accommodate the difference in totalizing rate and the rate at which bit errors could occur. If this buffer fills, loss of sync or loss of data line is presumed, and the following actions occur:

- The totalizer is inhibited.
- The buffer is forced to zero.
- Visual and audible alarms are activated.
- Automatic pattern resynchronization is initiated.
- When pattern sync is re-established, the buffer and totalizer are again enabled.

With this operating philosophy, and assuming operation at 2400 bps, an alarm will occur if an error burst (assuming 50-percent error rate) due to a dropout lasts longer than approximately 1.3 seconds, or if an error rate greater than 1×10^{-2} lasts for an extended period of time.

All test results were compiled from a number of 30 minute test runs and when an alarm condition occurred during the test run an "outage" was assumed to have occurred and the test run was not included in the final results. This method appeared to be quite reasonable since nearly all alarm conditions which were observed occurred when true fault conditions existed and data could not be transmitted for one reason or another.

TEST RESULTS

A program of regularly checking the performance of transmission circuits in the NASCOM network was instituted toward the end of 1966. Table 4 indicates the amount of data taken as of May 1, 1967, on circuits considered representative. Similar amounts of data have been taken on most other NASCOM circuits. Tests normally consist of amplitude and delay response runs using the Acton set, the measurement of levels at 1 khz, and noise measurements (random and impulse), all taken at each end of the circuit. In addition, a test run with data modems on the circuit using pseudo-random test data between Frederick 600 test sets was usually included.

Figures 11 and 12 represent a series of superpositions of Acton runs (amplitude and delay). The circuit to Honolulu showed only a small variation in characteristic over 4 months, but the Bermuda circuit showed quite wide deviations. This sample, plus many other similar tests, suggests that circuit attenuation and delay can be kept nearly constant over periods of months, but that current maintenance and operating techniques of the carriers do not guarantee this.

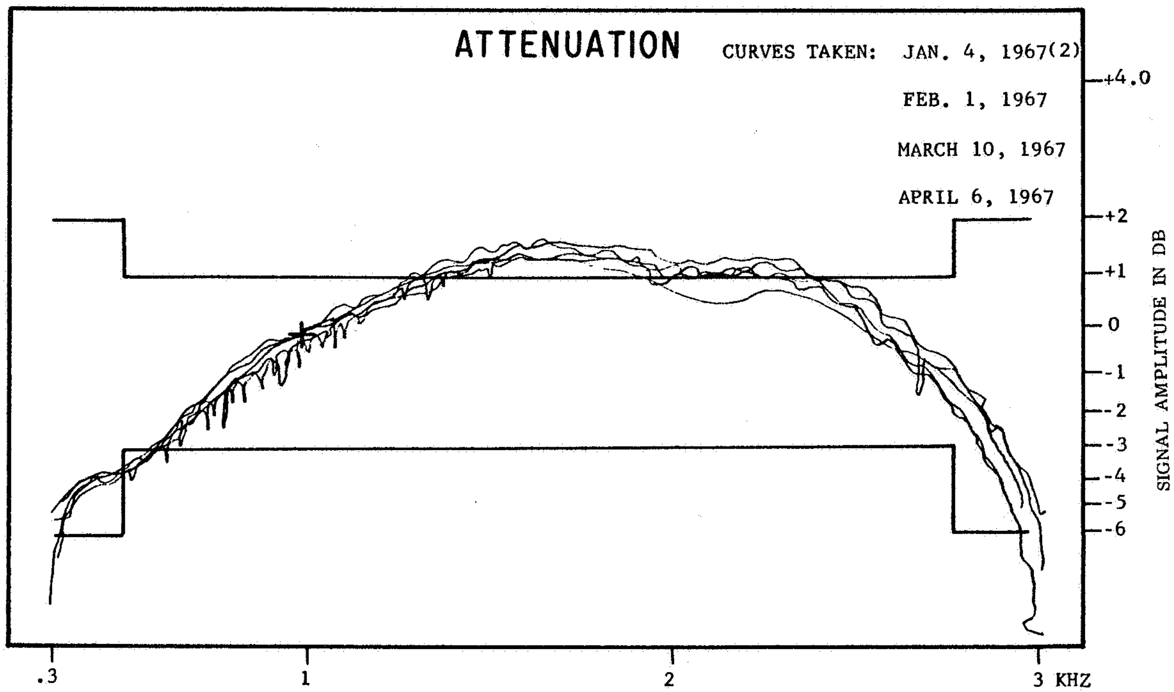
Variations of 3 db in overall loss at 1 khz were observed. Line-up procedures of the carriers and the use of automatic gain-controlling devices ensure that wider variations are unusual.

Frequency translation is not normally checked by NASA staff; it is usually small (less than the ±2 hz) and does not significantly affect the performance of modems now in use.

Dropouts so short that they do not require immediate maintenance are not presently measured on a regular basis, although they are known to exist. Tests by The Mitre Corp.[10] on a loop from Bedford, Mass. to Chicago and return gives an idea of the relative frequency and duration of dropouts. On submarine cable and satellite circuits the length of the circuit has little effect on this type of interference, and there is no reason to expect these sections to be any more

Table 4
Bit Error Rate Data Taken from
Selected NASCOM Data Circuits

CKT. NO.	TERMINAL REMOTE FROM GSFC	ONE WAY CIRCUIT LENGTH (MILES)	TYPE OF CIRCUIT	DIRECTION REF GSFC	NUMBER OF TESTS SINCE 1 JAN. 1967 ATTEN	NUMBER OF TESTS SINCE 1 JAN. 1967 DELAY	NUMBER OF TESTS BEFORE 1 JAN. 1967 ATTEN	NUMBER OF TESTS BEFORE 1 JAN. 1967 DELAY
30	CARNARVON	11,000	COMSAT	TX LOOP REC	- 1 2	- 2 2	- - -	- - -
26	CANBERRA	10,000	SUB-CABLE	TX LOOP REC	- 1 -	- - 1	- 1 3	- 1 3
27	CANBERRA	11,000	SUB-CABLE	TX LOOP REC	- 3 -	- 2 -	1 4 1	- 3 -
10	HONOLULU	4,850	SUB-CABLE	TX LOOP RX	2 1 4	2 1 4	- 2 1	- 1 1
13	HONOLULU	4,850	SUB-CABLE	TX LOOP RX	1 2 4	1 2 3	- 1 1	- 1 1
14	HONOLULU	4,850	SUB-CABLE	TX LOOP RX	1 2 4	- 2 4	- 1 1	- 1 -
29	GUAYMAS	2,300	MICROWAVE	TX LOOP RX	- 2 -	- 1 -	- 1 -	- 1 -
24	CORPUS CHRISTI	1,425	MICROWAVE	TX LOOP RX	- 2 -	- 1 -	- - -	- - -
28	BERMUDA	950	SUB-CABLE	TX LOOP RX	- 3 1	- 3 1	- 2 3	- 1 3
1	LONDON	3,700	SUB-CABLE	TX LOOP RX	- 4 4	- 4 4	- - 1	- - 1
3	LONDON	3,700	SUB-CABLE	TX LOOP RX	- 4 3	- 4 3	- - 1	- - 1



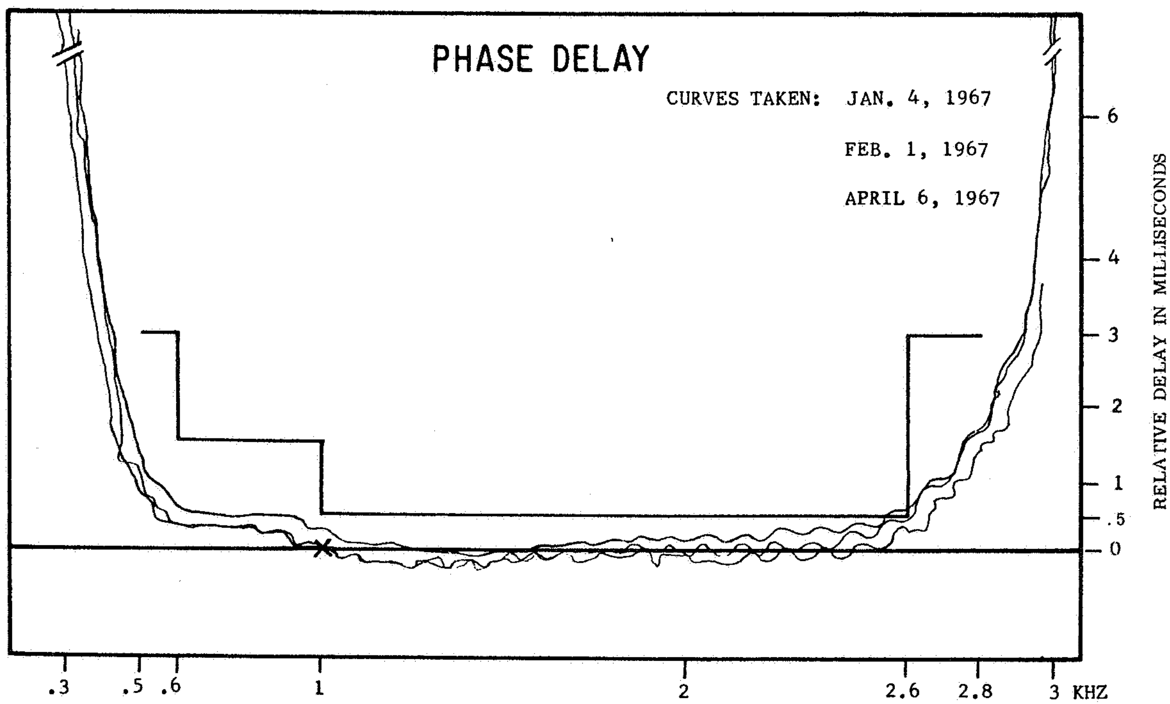


Figure 11. Honolulu Receive Circuit

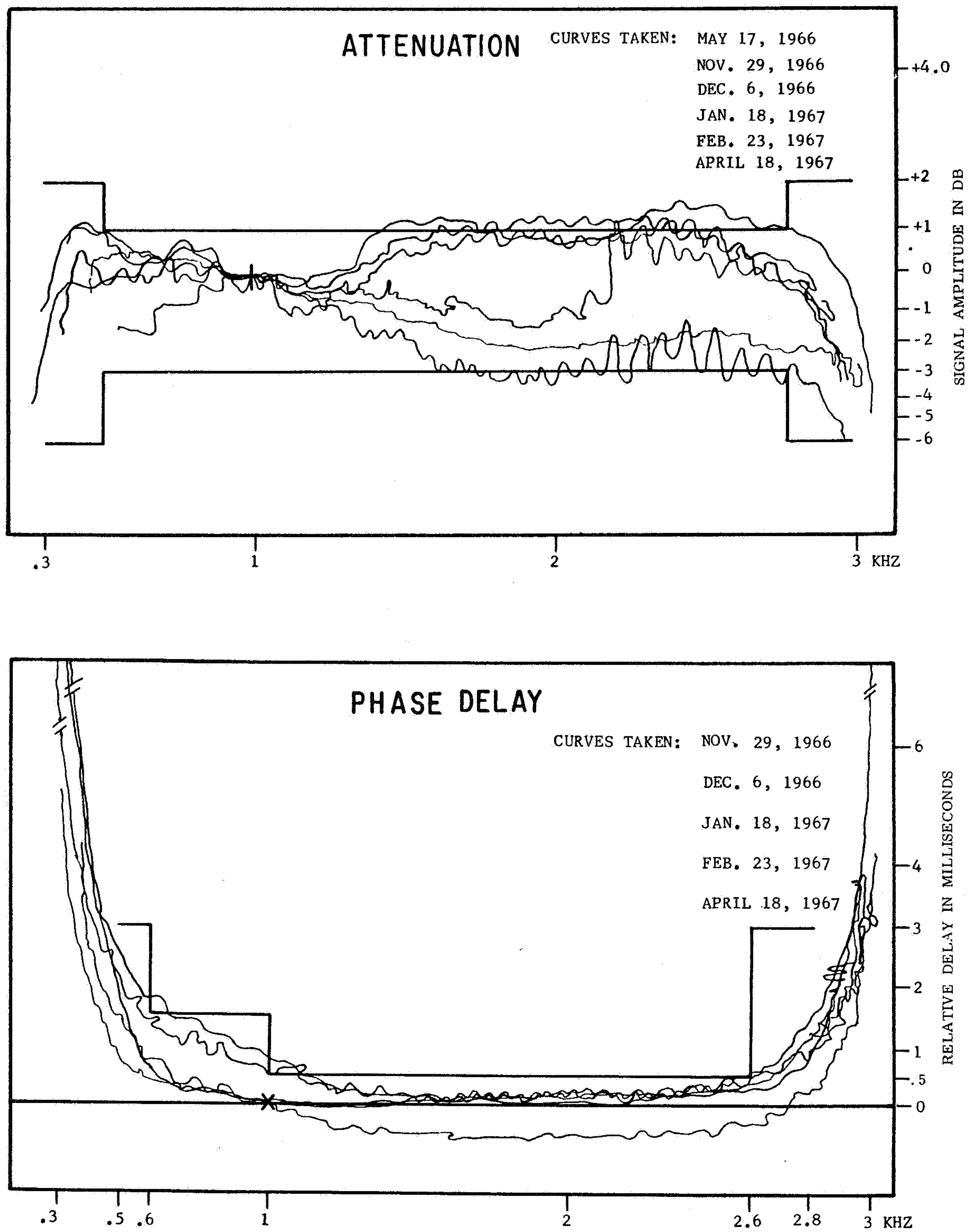


Figure 12. Bermuda Receive Circuit

prone to dropout interference than other types of links in a tandem arrangement. In face, there appears to be a case for relating the severity of this problem to the number of frequency-translation (modulation) points on a circuit and to the number of points where operators have access, rather than to the length of the circuit.

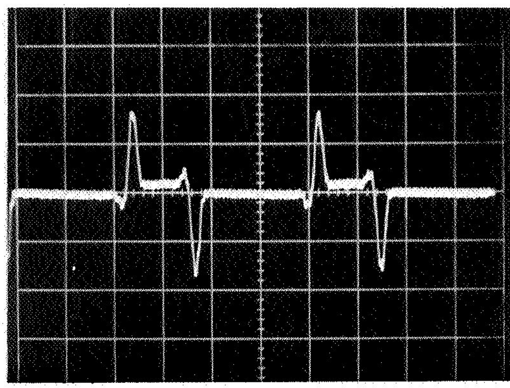
The use of an oscilloscope synchronized to an oscillator which slowly tracks the frequency of the received signal (Method 1) served to indicate that rapid phase changes did occur on long voiceband circuits. The more refined test, using the tracking oscillator of a bit synchronizer (Method 2), gave quantitative results which showed sudden (in about 1 millisecond) phase changes of 20 degrees on some circuits. It was expected that this would seriously impair the performance of a phase-modulated modem using four phases, but the WECO 205B modem has shown little or no susceptibility to phase jumps of this magnitude. However, when a 9600-bps wireline modem was tested, it was unable to follow this rate-of-change of phase (or frequency offset), and the performance was seriously degraded.

Measurements of phase jitter were made using the delay line and detector (multiplier) of a WECO 205B modem (Method 4). The most interesting results were obtained on a circuit from GSFC to Guaymas, Mexico, and back. The circuit was chosen for test because at the time it was suspected to have severe jitter. Figure 13 shows both the jitter (degrees in 833 microseconds) and the spectral analysis of this jitter. Further measurements indicated that the spectrum of the jitter did not change significantly in a period of one hour. The 60-hz component, which was not exactly at the frequency of the commercial power supply at GSFC, is prominent.

When a London circuit (GSFC to London and back) considered to be a typically stable circuit was checked in this manner, it was found that there was relatively little output from the discriminator most of the time. However, every few seconds (not regularly) a phase shift of 10 degrees or more would occur.

When an experimental 9600-bps modem was tested on each of two voiceband data circuits from Honolulu to GSFC, it was found to work well on one circuit but not on another, although performance with the 205B modem was nearly identical on both circuits. Both circuits met the 4B design goal. The phase jitter was checked, using the modified bit synchronizer method (Method 2), and rates of change of phase of up to 15 degrees per millisecond were observed on one circuit.

These two circuits, and a representative sample of other circuits, were checked for phase jitter using the MICOM flutter meter (Method 3). The output of this instrument is displayed on a meter and also made available as an



20° TRANSITIONS

13 a

—GUAYMAS CIRCUIT— CKT. NO. 29

CALIBRATION

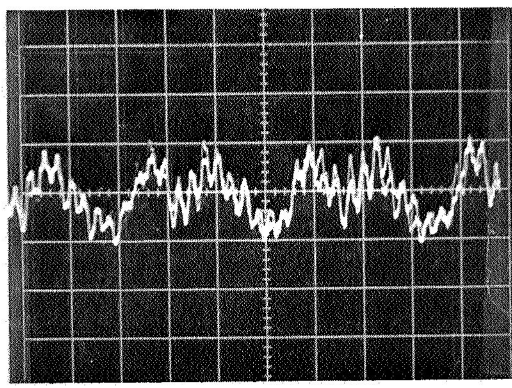
DATE: 30 DECEMBER 1966

L.P. FILTER: 2 KHz, 2 STAGES

VERT: 2V PER DIV.

HORIZ: 5ms PER DIV.

CARRIER: 1200 Hz.



13 b

PHASE JITTER

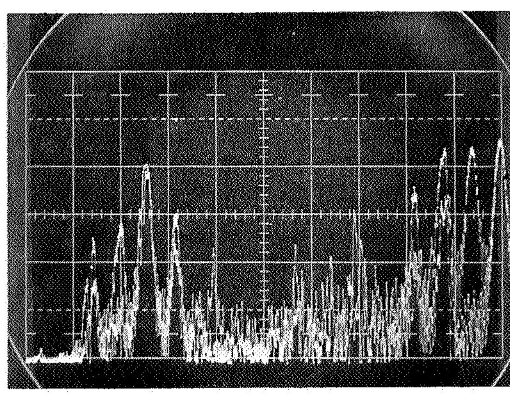
CARRIER: 1200 Hz

CARRIER LEVEL: 0dbm

VERT: 2V PER DIV.

HORIZ: 5ms PER DIV.

SCOPE SYNC: 60 Hz (LINE)



13 c

FREQ. SPECTRUM OF JITTER

HORIZ. RANGE: 1 KHz TO 0(L. TO R.)

VERT: 8db PER DIV.

SWEEP RATE: 5 SECONDS PER DIV.

Figure 13. Guaymas Circuit

electrical output. The output voltage is proportional to the percentage of frequency deviation from the frequency of the test tone. The output thus is per cent of frequency-dimensionally Hertz (cycles per sec.). Differentiating this output with respect to time would provide a useful measure of phase jitter effects.

In the test, the flutter (phase-jitter) output was presented to a spectrum analyzer sweeping at the rate of about 1 hz/sec, and spectra of the flutter were plotted on an X-Y recorder. The appendix shows the spectrum analysis of the phase jitter for several representative circuits. A 20-hz component, with harmonics, is noticeable on many circuits; on Canberra circuits, however, the predominant component is about 16-2/3 hz (one-third of the Australian power line frequency). As it is common practice to use ringing current at one-third of the power line frequency, it is probable that the ringing present in most telephone offices tends to modulate the frequency of the carrier-supply oscillators. The 60-hz component noted on the Guaymas circuits mentioned above was probably the same phenomenon, but was likely to have been caused by the mains themselves at some location where the mains frequency is not synchronous with that at GSFC.

Error rates on critical NASCOM circuits are regularly measured. Figures 14 and 15 are histograms of the errors recorded on some typical circuits. The Frederick 600 test set was used, and modems were WECO 205B. Error counts were read every 10 minutes, and then summed to obtain half-hour totals, which were plotted in histogram form. The height of the bars in Figures 14 and 15 which go to the top of the histogram field represent a number of errors equal to or greater than 1000. The histogram allows determination of diurnal variations or error rate, but does not show whether the errors during any half-hour showing an unduly high error rate were concentrated in one burst, or distributed relatively widely through a large proportion of the half-hour. In fact, the errors do usually come in bursts, and a large percentage of the half-hour may indeed have quite a low error rate. Tests are under way which will give an indication of the short-term distribution of errors and bursts of errors. Results of these tests are not yet available. It is hoped, however, that definite patterns will emerge which will enable a more realistic use of the readings taken on the Frederick 600 sets.

Table 5 summarizes error performance for a 3-month period for several representative circuits in the NASCOM network.

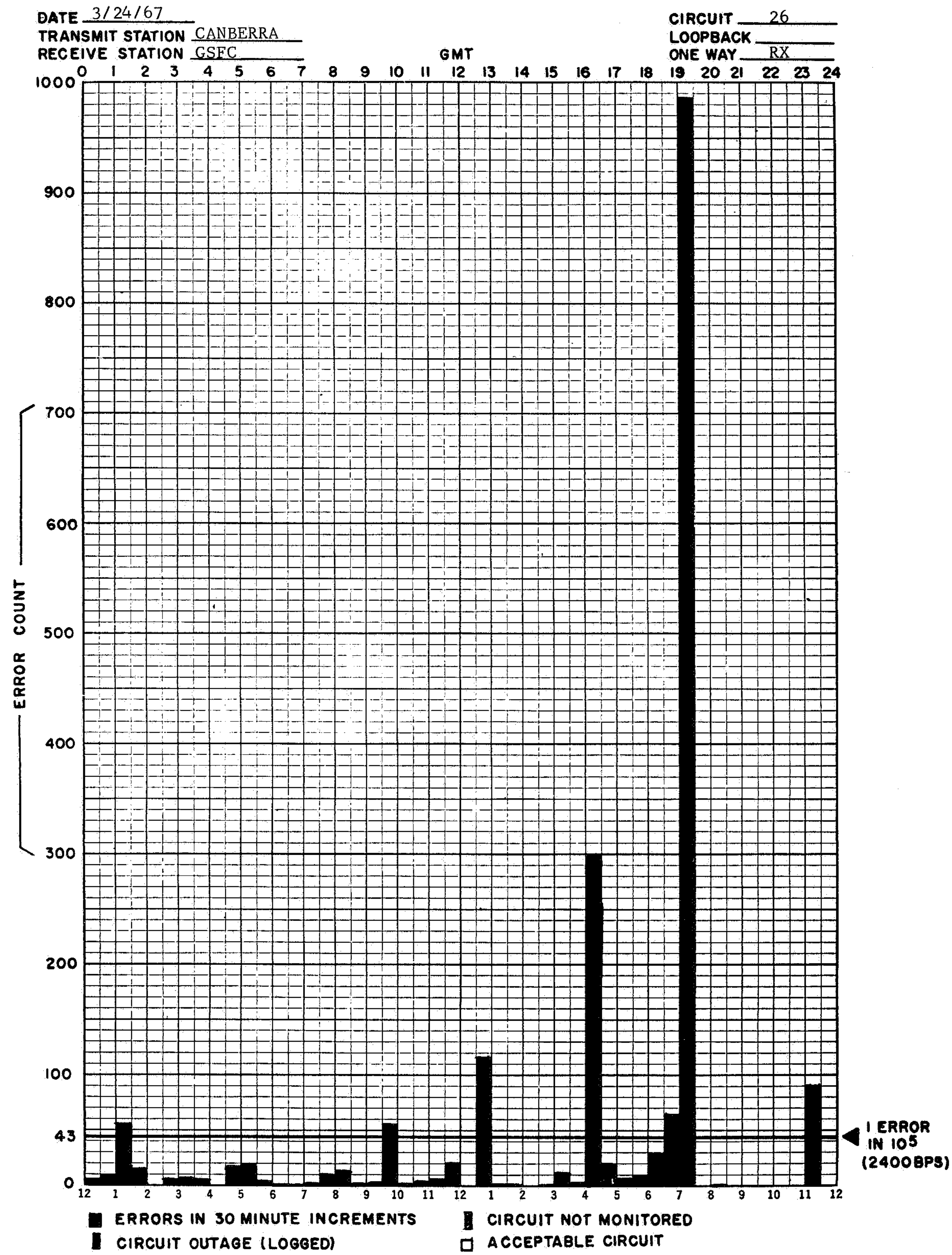


Figure 14. Histogram of Error Rate, Circuit #26

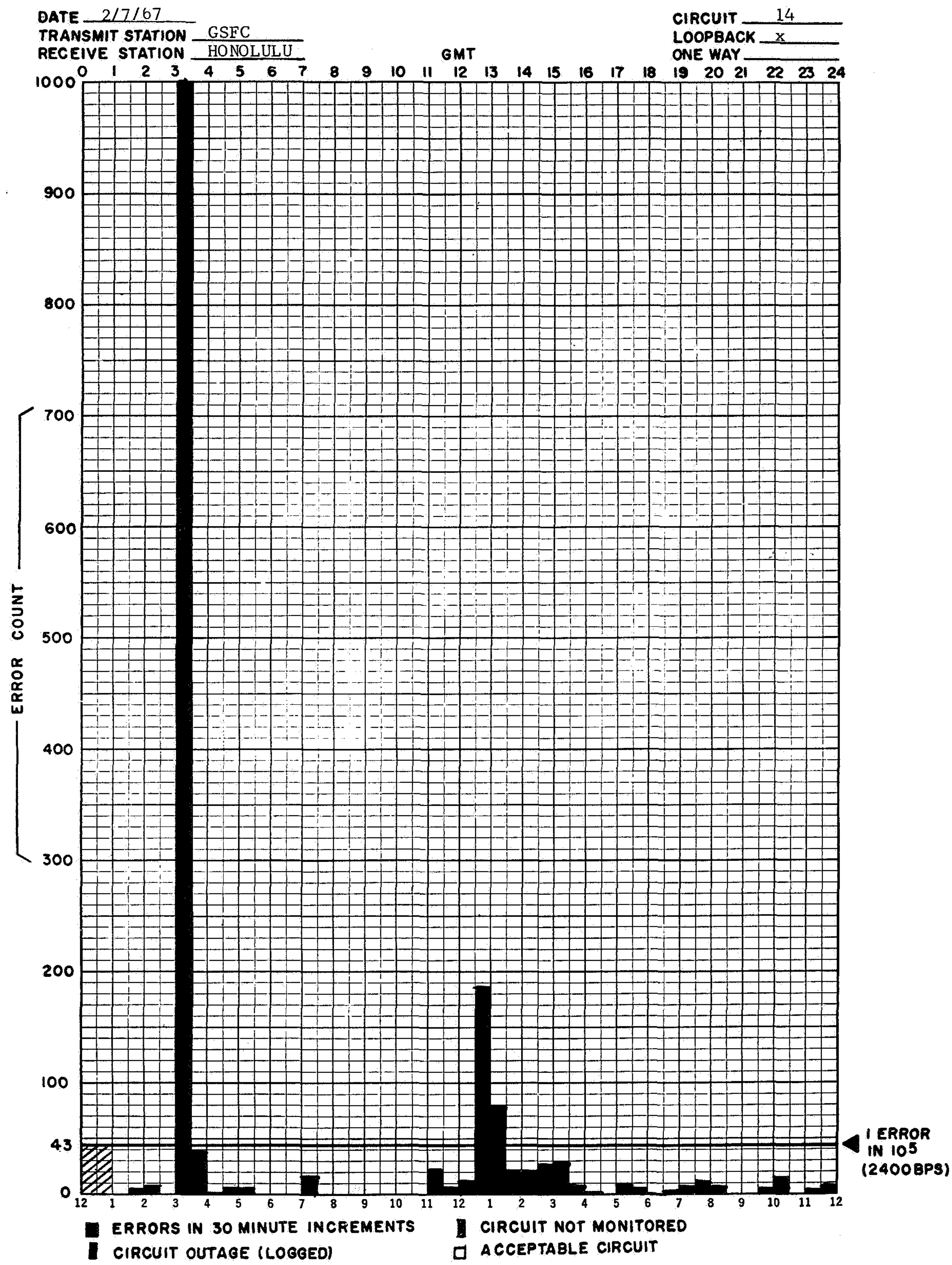


Figure 15. Histogram of Error Rate, Circuit #14

Table 5
Summary of Error Performance
for Selected NASCOM Data Circuits

CKT #	Remote Terminal Location	Test Direction*	Total Test Data Hours (for QTR)	Error Rate			
				Feb	Mar	Apr	QTR
1	London	TX	63.5		1.6×10^{-6}	8.2×10^{-6}	5.7×10^{-6}
		RX	63.0		1.7×10^{-6}	7.2×10^{-6}	5.2×10^{-6}
3	London	TX	48.0		8.3×10^{-6}	3.3×10^{-5}	2.1×10^{-5}
		RX	47.5		1.0×10^{-6}	1.4×10^{-6}	1.2×10^{-6}
10	Honolulu	TX	43.5		1.1×10^{-6}	2.7×10^{-6}	1.8×10^{-6}
		RX	43.0		1.6×10^{-6}	1.2×10^{-6}	1.4×10^{-6}
13	Honolulu	TX	47.0		3.6×10^{-6}	2.1×10^{-5}	1.2×10^{-5}
		RX	46.0		3.5×10^{-6}	4.4×10^{-6}	3.9×10^{-6}
14	Honolulu	TX	48.0		1.6×10^{-6}	2.8×10^{-6}	2.2×10^{-6}
		RX	48.0		5.0×10^{-6}	6.5×10^{-6}	5.7×10^{-6}
21	Canberra	TX	24.0			4.7×10^{-6}	4.7×10^{-6}
		RX	24.0			3.1×10^{-6}	3.1×10^{-6}
22	Canberra	TX	69.5		2.3×10^{-5}	1.1×10^{-5}	1.9×10^{-5}
		RX	68.5		6.9×10^{-6}	3.3×10^{-6}	5.7×10^{-6}
24	Corpus Christi	TX	45.0		3.4×10^{-6}	8.5×10^{-7}	2.2×10^{-6}
		RX	37.5		1.9×10^{-4}	2.6×10^{-6}	6.9×10^{-5}
26	Canberra	TX	69.0		9.1×10^{-6}	2.3×10^{-5}	1.4×10^{-5}
		RX	67.5		1.6×10^{-5}	1.2×10^{-5}	1.5×10^{-5}
27	Canberra	TX	69.0		9.1×10^{-6}	2.3×10^{-5}	1.4×10^{-5}
		RX	67.5		1.6×10^{-5}	1.2×10^{-5}	1.5×10^{-5}
28	Bermuda	TX	23.0			5.5×10^{-7}	5.5×10^{-7}
		RX	24.0			4.7×10^{-6}	4.7×10^{-6}
29	Guaymas	TX	69.5		7.2×10^{-5}	5.6×10^{-5}	6.6×10^{-5}
		RX	71.0		8.1×10^{-6}	7.6×10^{-4}	3.0×10^{-5}
30	Carnarvon (via COMSAT)	TX	51.0	2.0×10^{-5}		9.6×10^{-5}	5.2×10^{-5}
		RX	30.5	1.8×10^{-5}			1.8×10^{-5}
31	Carnarvon (via land-line)	TX	36.0	4.7×10^{-5}		5.2×10^{-5}	4.9×10^{-5}
		RX	37.0	6.4×10^{-5}		4.0×10^{-5}	5.4×10^{-5}

*As determined at the GSFC end of the circuit.

CONCLUSIONS

The tests and studies described here have led to the following conclusions:

1. Where 4B quality circuits can be provided and maintained on overseas long-haul channels, error rates of 1×10^{-5} or better can be obtained quite consistently at 2400 bps using the WECO 205B data modem.

2. Arranging 4B circuits in tandem in order to provide extremely long-haul facilities (typically over 10,000 miles) is quite successful, as long as data regeneration is accomplished at the points where the circuit segments meeting 4B design goals interconnect.

3. Common carriers have taken a great interest in the goals of NASCOM. The prevailing atmosphere of cooperation among all carriers involved has permitted establishment of quite long channels, traversing up to three different areas of common carrier control, which meet 4B design goals end-to-end.

4. Circuits provided in accordance with the 4B design goals typically exhibit quite stable amplitude-response and envelope-delay characteristics. Short-term error rates do vary considerably, however; when the performance falls below 1×10^{-5}, it tends to fall significantly below, typically two orders of magnitude or worse. This is because of sudden changes of other channel parameters such as impulse noise and net loss (short dropouts). Sudden phase changes (incidental frequency modulation) are apparently not a significant factor in causing the observed bit-error rates at 2400 bps, but this characteristic appears to be the principal cause of errors at data rates approaching 9600 bps.

SUMMARY

It is becoming apparent that the original design goal for a long-term end-to-end bit error rate of 1×10^{-5} can be met on a complex worldwide data-communications system such as NASCOM. When channel failures do occur, however, they tend to be catastrophic whether the failure is short-term or long-term. Plans now under way to accumulate a substantial amount of fine-grain analysis of actual channel parameters during transmission of data and measurement of error rate may reveal trends in these parameters that can signal impending failure.

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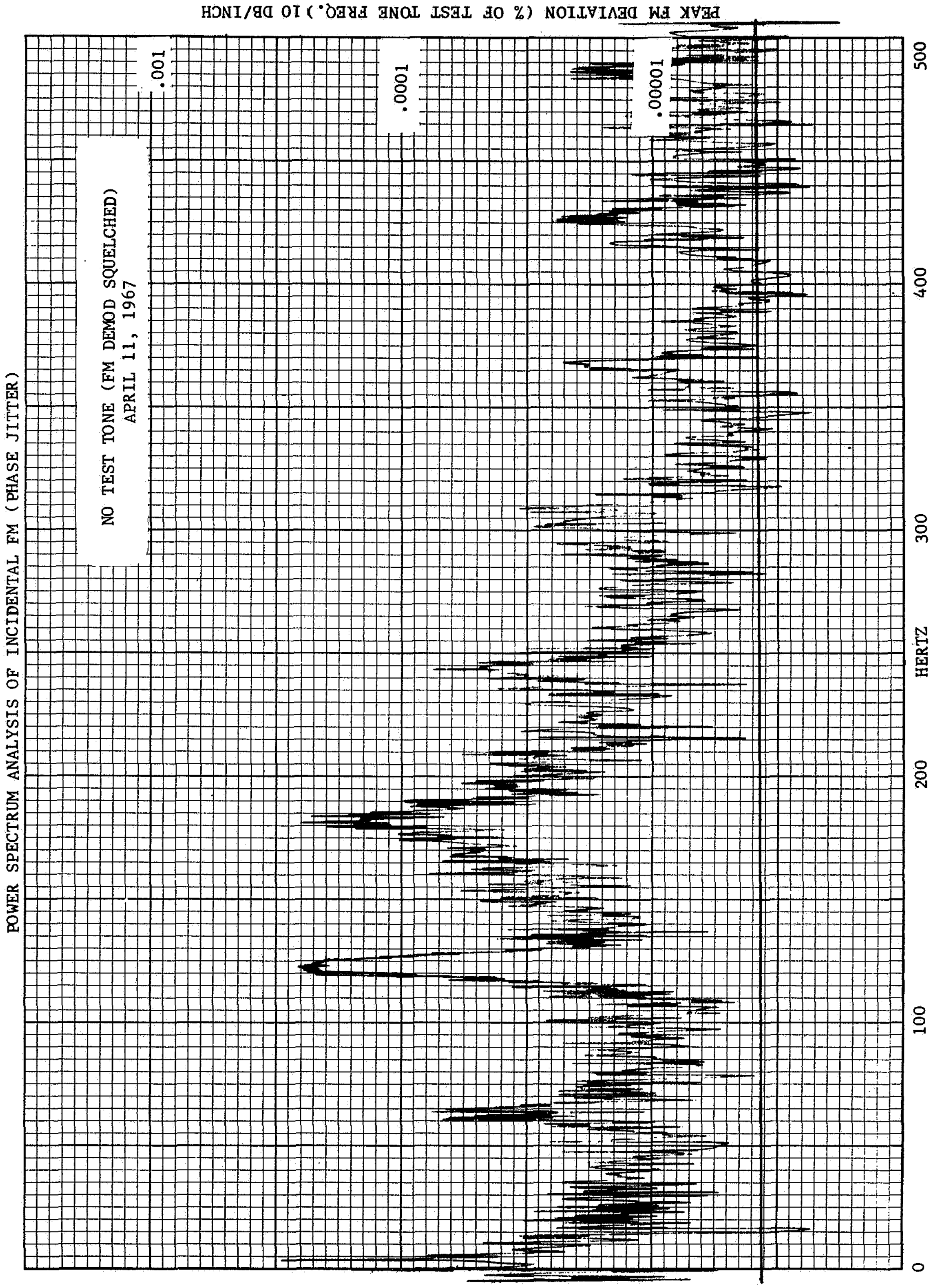
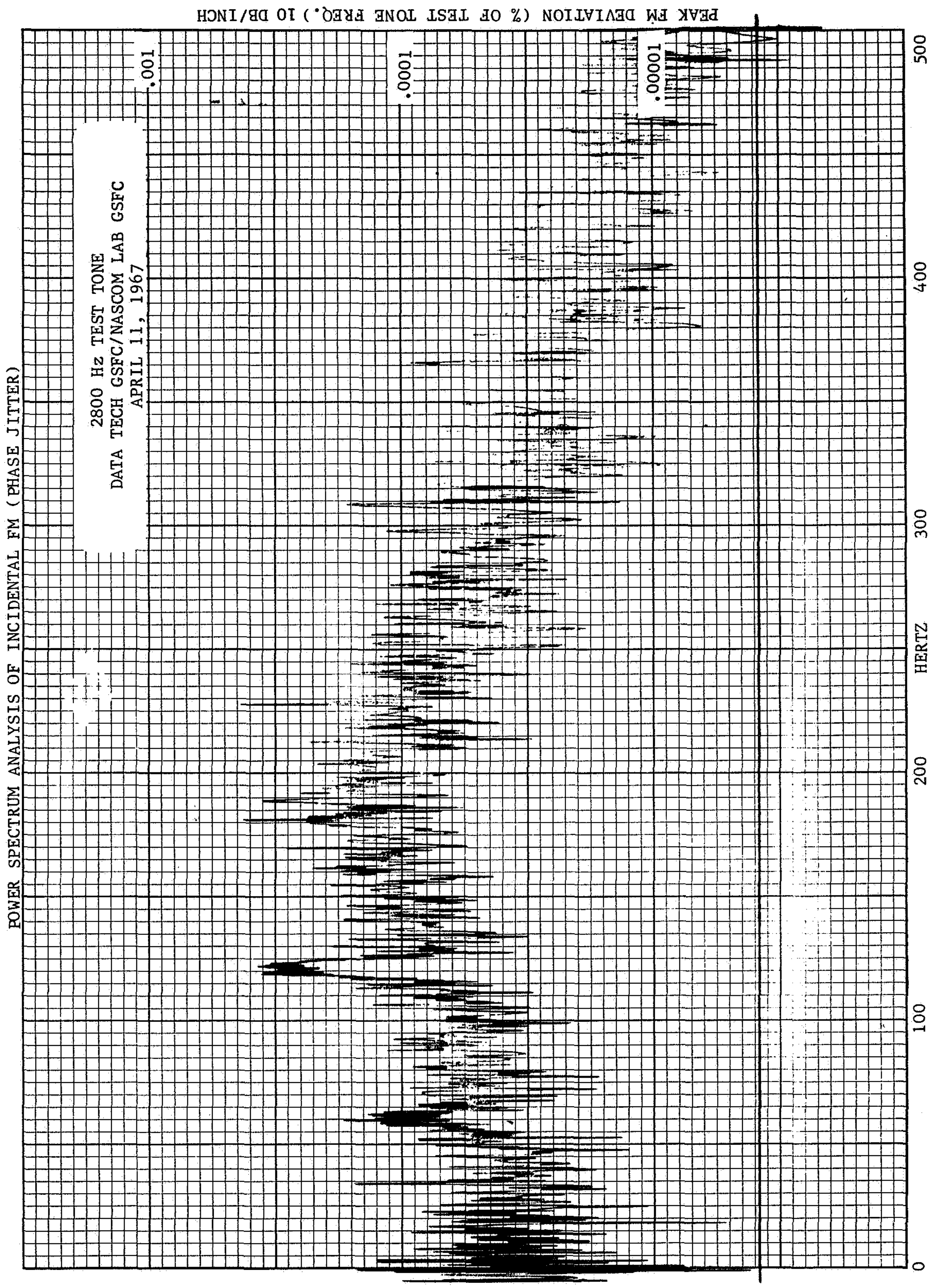
APPENDIX

Spectrum Analyses of Phase Jitter for Representative NASCOM Circuits



POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
NO TEST TONE (FM DEMOD SQUELCHED)
APRIL 11, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) 10 DB/INCH
.001
.0001
.00001
0
100
200
300
400
500
HERTZ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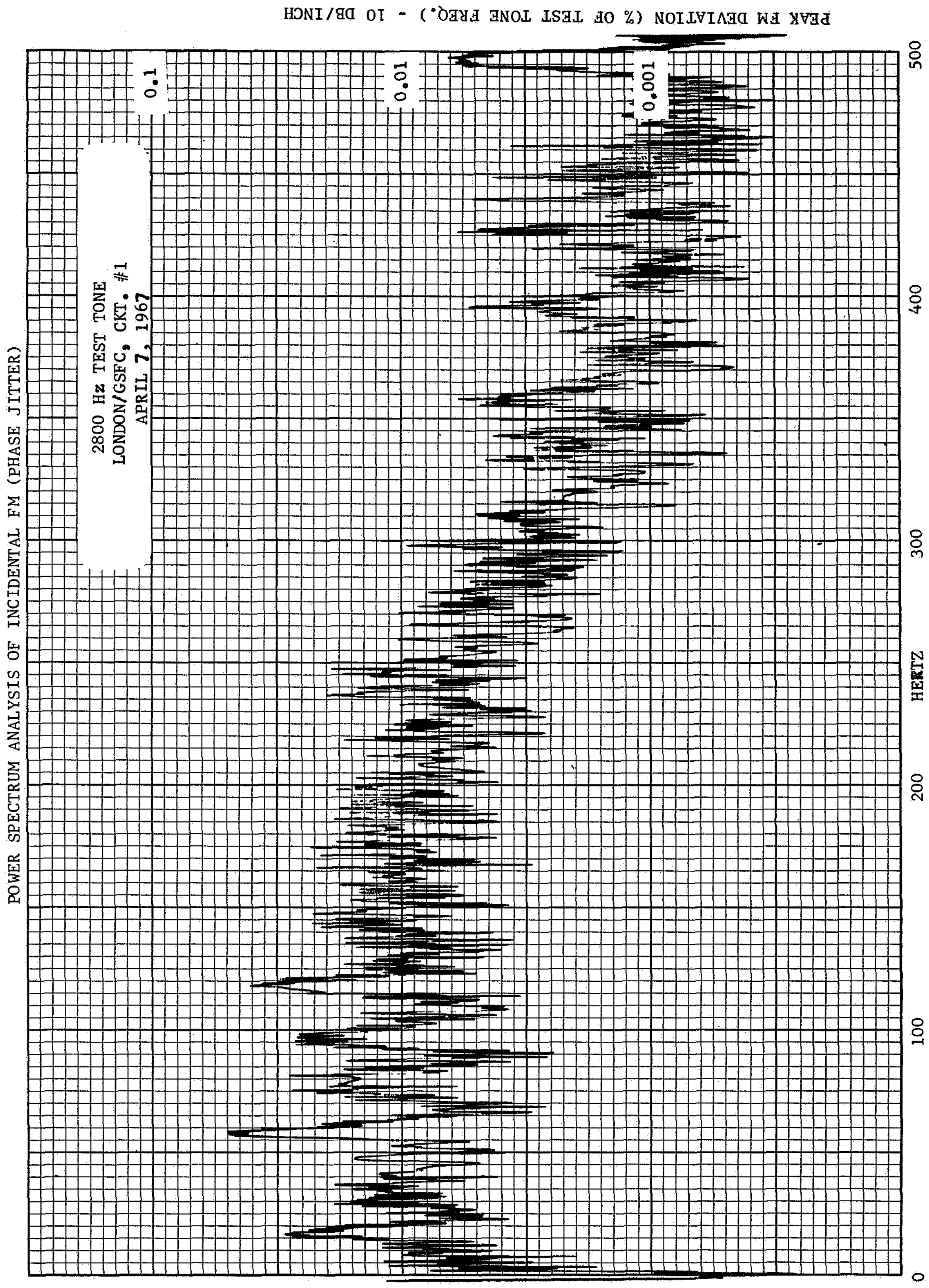
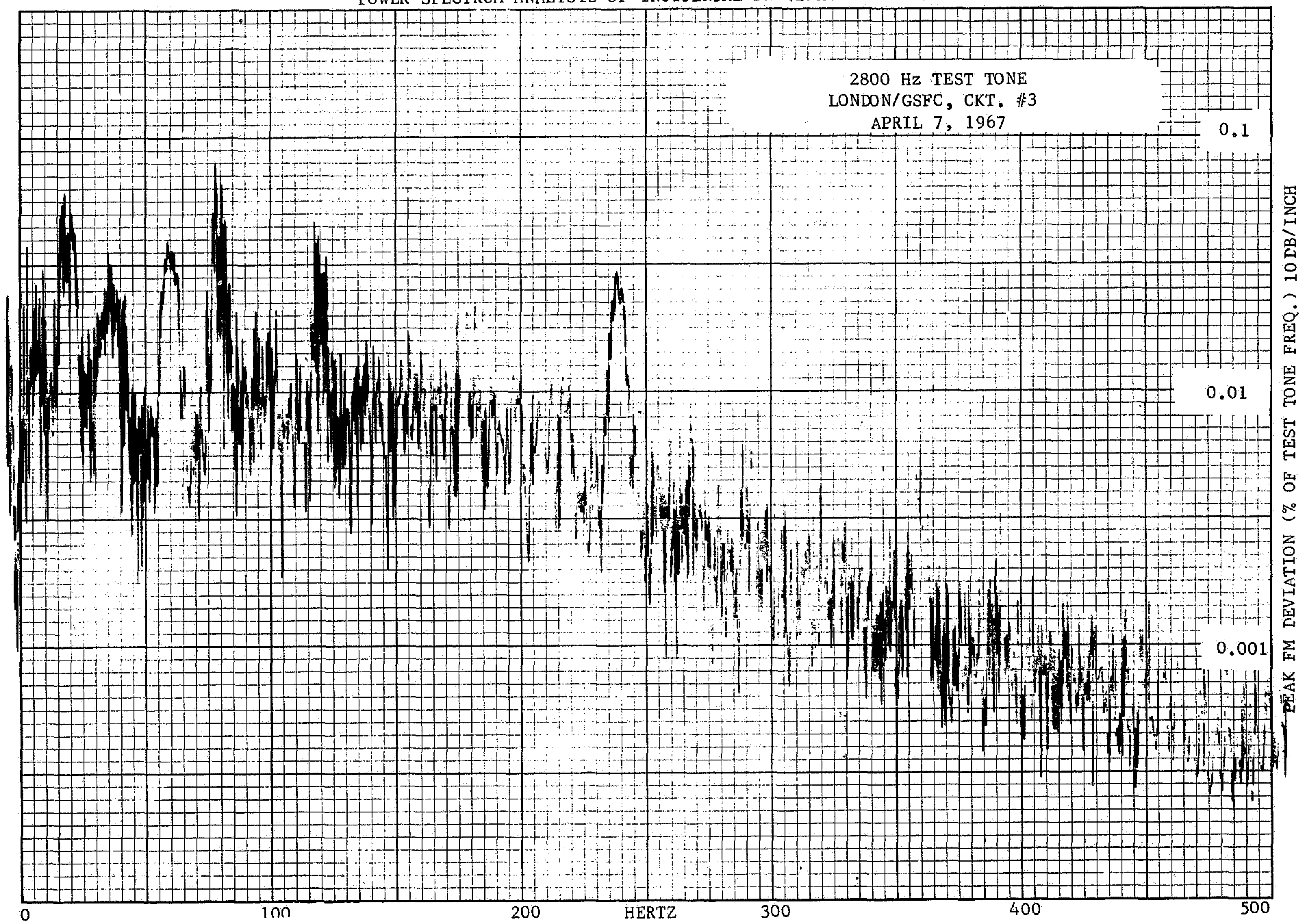
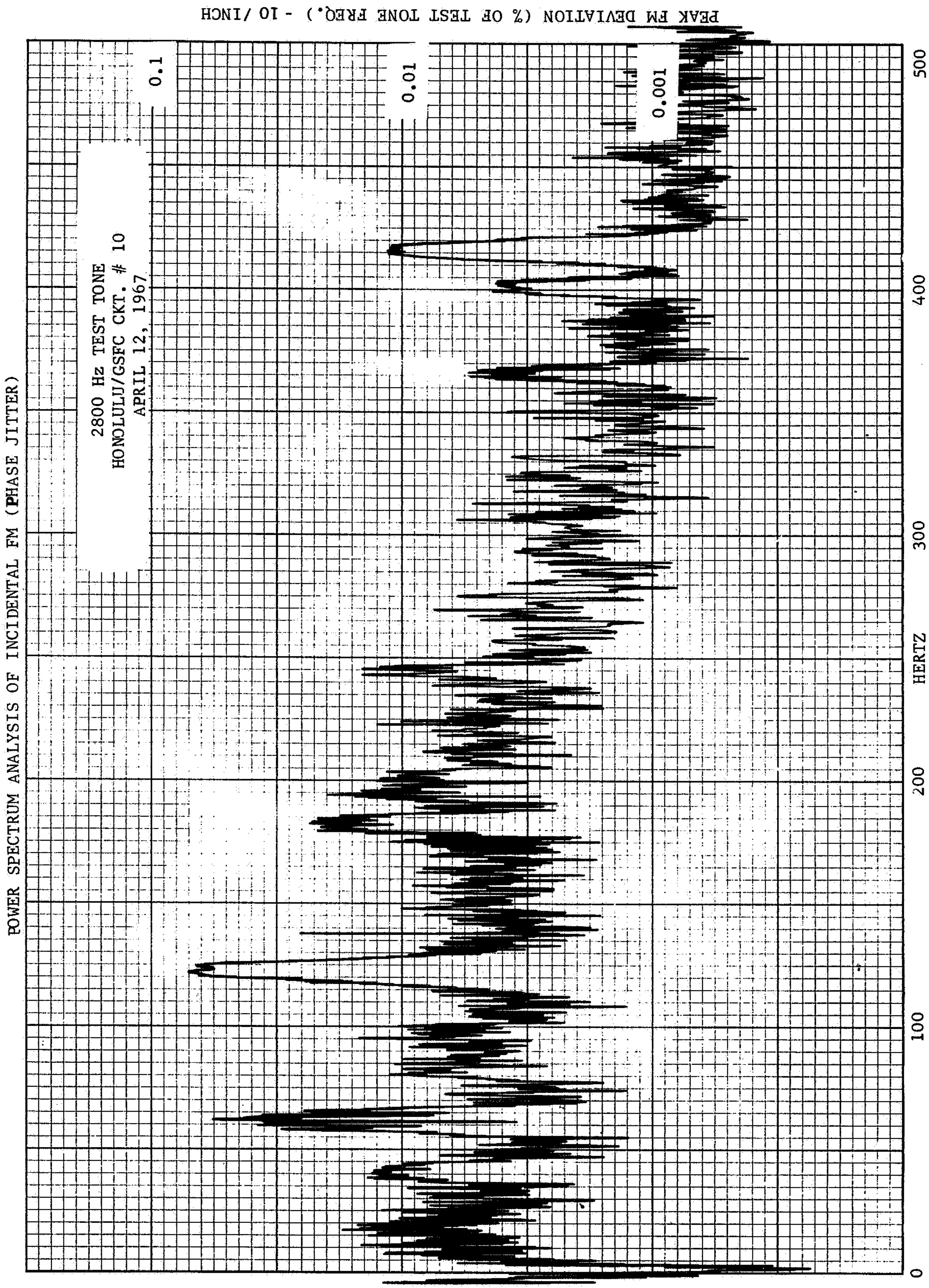
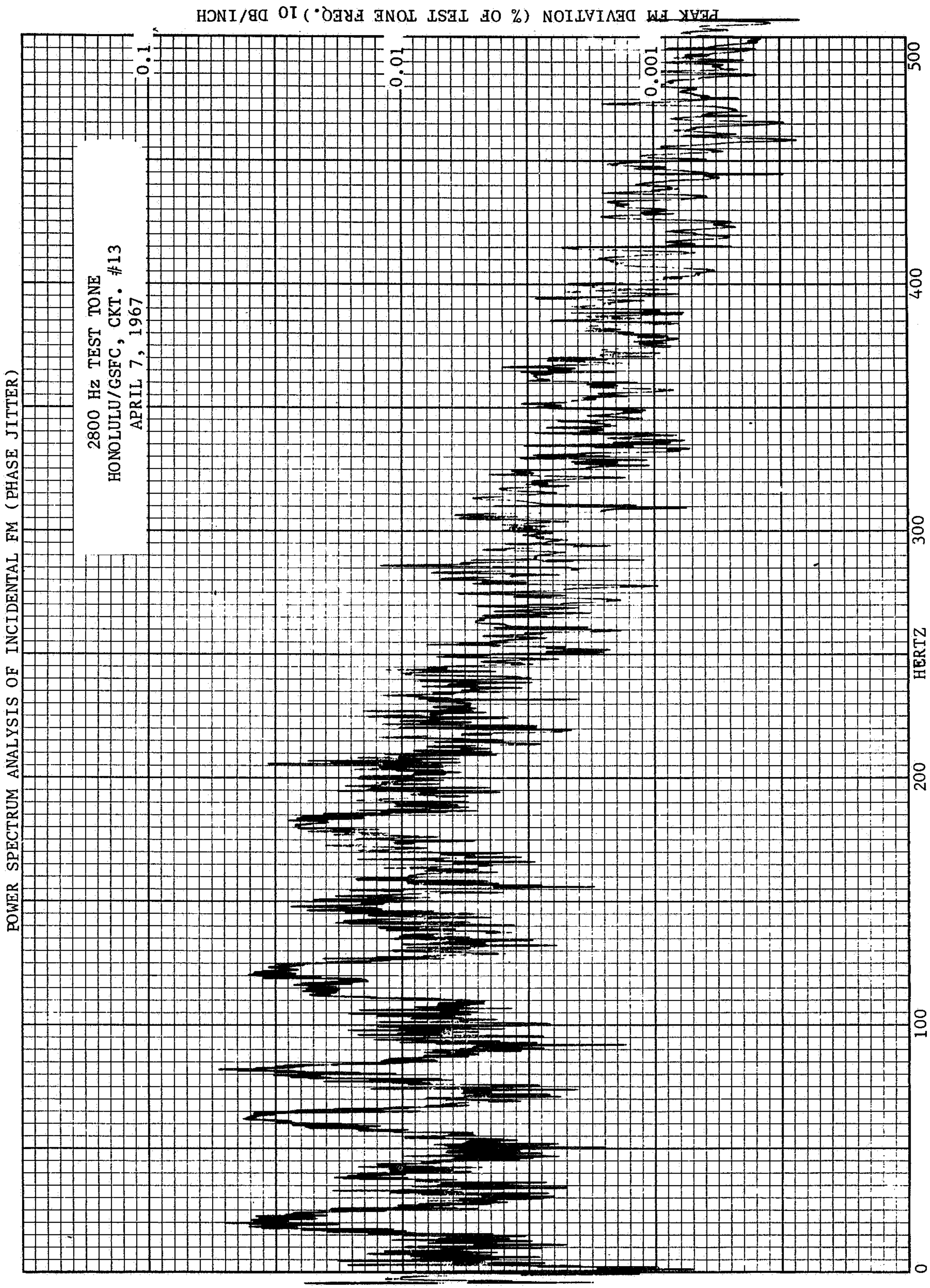
2800 Hz TEST TONE
DATA TECH GSFC/NASCOM LAB GSFC
APRIL 11, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) 10 DB/INCH
.001
.0001
.00001
0
100
200
300
400
500
HERTZ

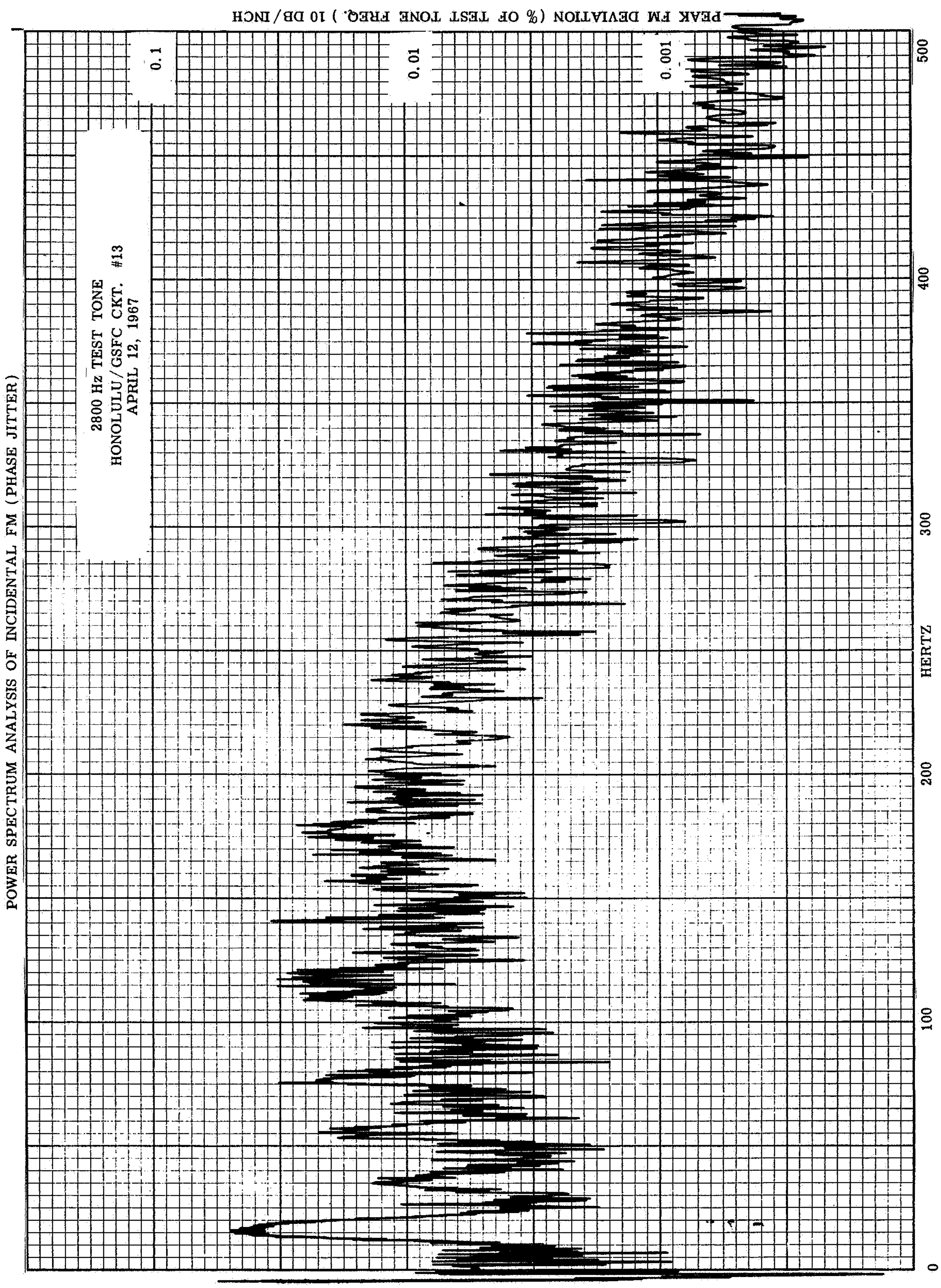

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
LONDON/GSFC, CKT. #1
APRIL 7, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) - 10 DB/INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)

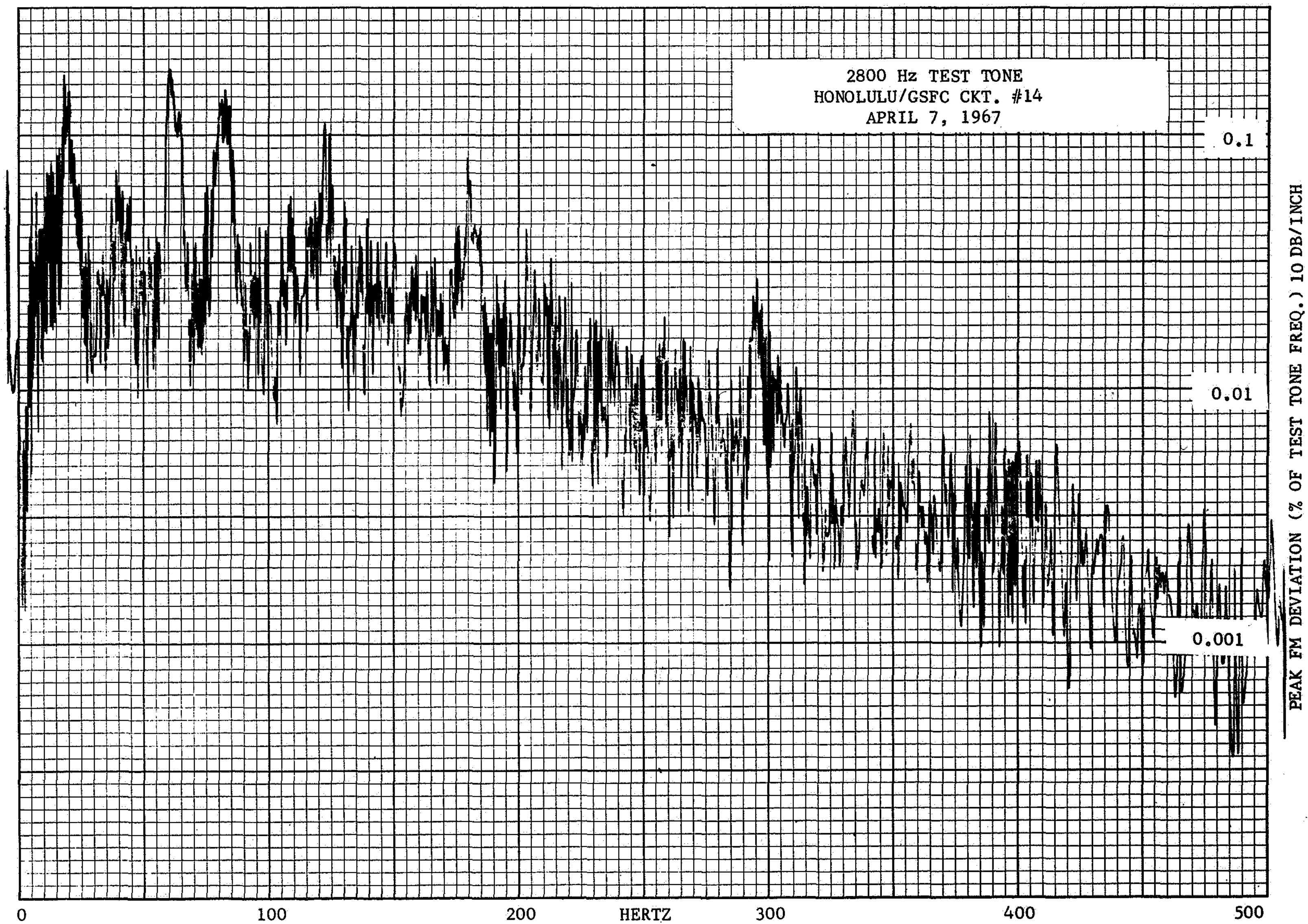


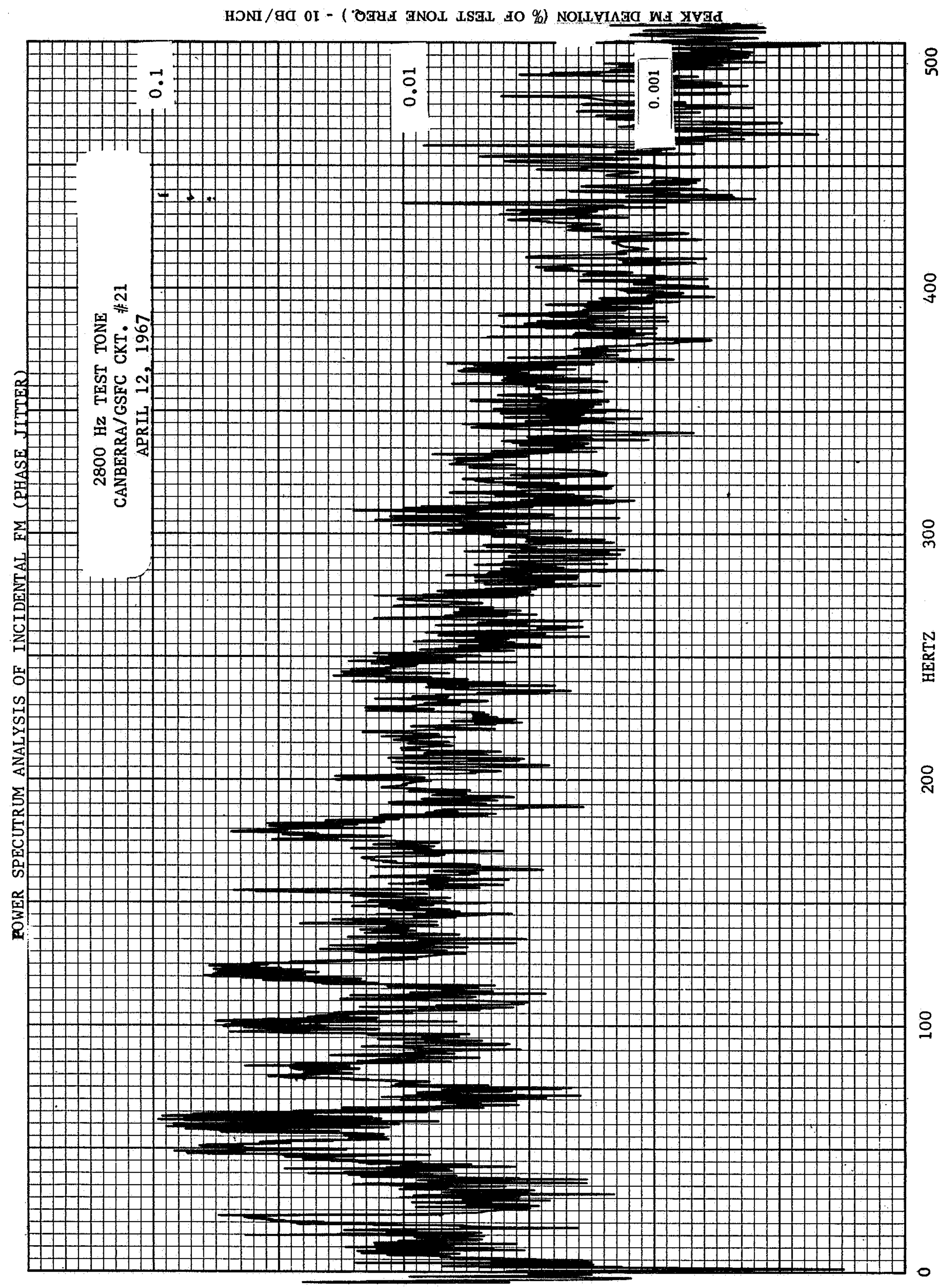

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
HONOLULU/GSFC CKT. # 10
APRIL 12, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) - 10 /INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500

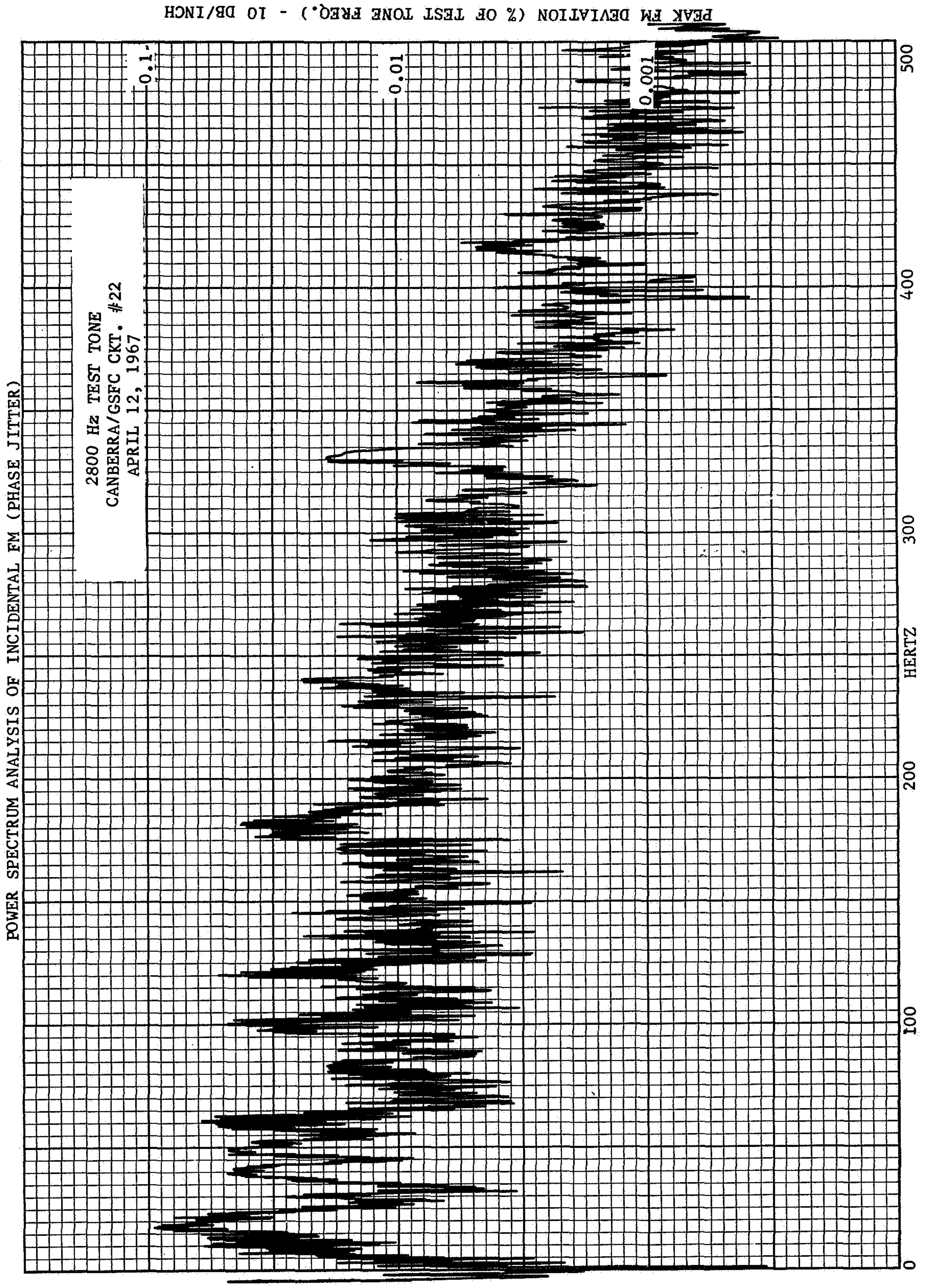

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
HONOLULU/GSFC, CKT. #13
APRIL 7, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) 10 DB/INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500


POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
HONOLULU/GSFC CKT. #13
APRIL 12, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) 10 DB/INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)




POWER SPECUTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
CANBERRA/GSFC CKT. #21
APRIL 12, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) - 10 DB/INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500



POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)
2800 Hz TEST TONE
CANBERRA/GSFC CKT. #22
APRIL 12, 1967
PEAK FM DEVIATION (% OF TEST TONE FREQ.) - 10 DB/INCH
0.1
0.01
0.001
HERTZ
0
100
200
300
400
500

POWER SPECTRUM ANALYSIS OF INCIDENTAL FM (PHASE JITTER)